Role of Special Feature in Side Resistance of a Model Steel Pile

Thesis Submitted to the University of Delhi

for the Award of the Degree of

Doctor of Philosophy

in

Civil Engineering

Submitted by

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(Ref. No FT / Ph.D. / 10241)

University of Delhi, Enrolment No.Ph.D. - 49/2009

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September 2015

CERTIFICATE

This is certified that the thesis entitled, "Role of Special Feature in Side Resistance of a Model Steel Pile", by Naresh Kumar(Ref. No FT / Ph.D. / 10241) for the fulfilment of the requirements for the award of the degree in,"Degree of Philosophy" in Department of Civil Engineering", Faculty of Technology, University of Delhi, Delhi-110042 is the original work carried out by the candidate during the period from September 2009 to September 2015 under my supervision and guidance.

The work embodied in this thesis has not been submitted for the award of any other degree in any university.

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Certificate of Originality

The research work embodied in this thesis entitled "Role of Special Feature in Side Resistance of a Model Steel Pile" has been carried out by me at the Department of Civil Engineering, Faculty of Technology, University of Delhi, Delhi, India. The manuscript has been subjected to plagiarism check by Turnitin Software. The work submitted for consideration of award of Ph.D. is original.

(Naresh Kumar)

In the loving memory of

My parents

Dedicated

To

Nature

ACKNOWLEDGMENT

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ABSTRACT

The steel piles have the advantages of being robust, light to handle, capable of carrying high compressive and tensile loads when driven to a varied stratum, capable of being driven to a deep level to reach a bearing stratum and to develop a high frictional resistance, although, their cost per metre run is relatively high compared with precast concrete piles. The frictional resistance of pile is known as side resistance of pile in the literatures on piles.The main contribution of this work to the body of knowledge is introducing invented special feature which resulted in increase in side resistance of a model steel pile and that, too, with almost minimum disturbance of the soil (air and sun dried sand has been considered in the present wok) while introducing a special feature. Described herein is a slotted holes, mesh-filtered; mesh-plugged steel pile (patented by Kumar and Trivedi, 2013a, b) having a pattern of regular or zig-zag orthogonal spikes (spiking out from the lateral surface of the pile in orthogonal or in inclined direction at varied angles) that can be used in a variety of soil conditions as well as in apparatus and associated methods.

In saturated and submerged soils (pore pressure measurements are not considered in the present thesis), slotted holes helps in increase of effective stresses in soil-steel pile surface interaction by draining out extra build-up of pore water pressure in the immediate and longer run of time under the structural loading pressure. Flow of water at higher potential will not be outwards from the lateral surface of the steel pile, but, inwards to inside of steel pile through slotted holes of steel pile. These slotted holes are on the entire lateral surface of steel pile except conical surface at the bottom of steel pile. It reduces the chances of build-up of excess pore water pressure for liquefaction of soils in the radial stressed zones of interaction of soil-steel pile. As effective stresses are directly proportional to shear strength of the soil mass so, any reduction of pore water pressure through slotted holes of mesh- filtered steel pile or lead to increase of side-resistance on soil-steel pile surfaces.

The side-resistance which is a part of load carrying capacity of steel piles tend to increase to a large extent due to increase of effective stresses on soil-steel pile interface. This is further increased due to presence of slotted holes on the outer lateral surface of the steel pile which not only drains out pore water to inside of the steel pile through mesh filter slotted holes, mesh-filtered; mesh-plugged steel pile but also increase frictional forces due to roughness induced on the surface. Further, this work considered the effect of orthogonal as well as inclined spikes, which in totality due to interlocking arrangement of spikes with the soil, lead to increase in side resistance.

The whole arrangement of providing slotted holes, spikes along with doubly sloped circular fins on lateral surface at regular intervals, increased the side resistance of the steel pile, increased the density of adjoining soil mass, and consolidated the soft soil, thereby, improving the safety factor for designed loads of super-structures, making it usable for construction of deep foundation unit. The dewatering unit (not discussed in this thesis) as patented by Kumar and Trivedi (2013 a, b)is attached through a pipe from the top-most slotted hole of the steel pile which act to remove the drained out water collected in-side the conical-tip of slotted hole-cum-spiked steel pile. This special feature of slotted holes-cum-spikes was provided throughout the vertical lateral surface of the model steel pile.

This work has introduced an improvement factor, ξ, which numerically captures the potential increase in the load carrying capacity of a model steel pile in the context of in side resistance due to special feature i.e. slotted holes, spikes and fins. The side resistance increased due to length of spike, diameter of spike and inclination of spike (maximum at 60° in the direction of application of force). The following parameters were kept fixed w.r.t. number of spikes, spacing between the spikes in a row, vertical spacing between the spikes, pattern of the spikes (i.e. zig-zag or regular pattern), shape of the spikes (cylindrical), taper of the spikes (0° in the present work because of cylindrical spikes), surface roughness of the spikes in the form of threaded pattern on the surface on the spikes coming through welded nuts. The spike inclination, β, w. r. t. vertical plumb line is defined as any angle at a point on a model steel pile between outside upward plain surface of a model steel pile and inclined spike and varies in the range 0º< β <180º for the vertical direction at specified constant angular intervals of 30º, where β=30º, 60º, 90º, 120º and 150º) were considered in increasing order in the clockwise direction when spikes were to be seen on the right of the vertical axis of upright direction of the model steel pile.

There was an increase in side-resistance of a model steel pile which leads to significant increase of load carrying capacity of the model steel pile. Providing a special feature such as, whole arrangement of providing slotted holes, spikes and that, too, at various inclinations from 30º to 150º, along with doubly sloped circular fins on lateral surface at regular intervals, on a model steel pile, not only increased side resistance but also increased load carrying capacity of a model steel pile. It made the specially featured i.e. slotted-cum-spiked-cum-doubly sloped finned (facing vertically upwards) model steel pile is not only a user-friendly but an economical one also (due to lesser overall cost of per meter run of a special featured steel pile when compared for an equivalent load carrying capacity of per meter run of a plain model steel pile).

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LIST OF SYMBOLS

1. ß - Beta – Apparent angle of inclination of spikes at a point w.r.t. positive direction of vertical plumb line. Real angle of inclination = ß +/- θ
2. θ – Theta - Angle of taper of lateral surface of a model steel pile at a point w.r.t. Positive direction of vertical plumb line - (+ ve for inward i.e. angle between tapered surface towards the central axis of model steel pile and positive direction of vertical plumb line) and vice-versa.
3. ξ – zeta – An improvement factor - a ratio of side resistance of special featured model steel pile to that of plain model steel pile
4. MSP - Mild steel pile
5. Spike 02/10 – Spikes at 90º from lateral surface of model steel pile having length 02 cm and dia. 10 mm.
6. Spike 04/10 – Spikes at 90º from lateral surface of model steel pile having length 04 cm and dia. 10 mm.
7. Spike 06/10 – Spikes at 90º from lateral surface of model steel pile having length 06 cm and dia. 10 mm.
8. Spike 08/10 – Spikes at 90º from lateral surface of model steel pile having length 08 cm and dia. 10 mm.
9. Spike 10/10 – Spikes at 90º from lateral surface of model steel pile having length 10 cm and dia. 10 mm.
10. Spike 02/08 – Spikes at 90º from lateral surface of model steel pile having length 02 cm and dia. 08 mm.
11. Spike 04/08 – Spikes at 90º from lateral surface of model steel pile having length 04 cm and dia. 08 mm.
12. Spike 06/08 – Spikes at 90º from lateral surface of model steel pile having length 06 cm and dia. 08 mm.
13. Spike 08/08 – Spikes at 90º from lateral surface of model steel pile having length 08 cm and dia. 08 mm.

14. Spike 10/08 – Spikes at 90º from lateral surface of model steel pile having length 10 cm and dia. 08 mm.
15. Spike 10/10 at 30º – Spikes from lateral surface of model steel pile having length 10 cm and dia. 10 mm with their angle of inclination of 30º at a point w.r.t. positive direction of the vertical plumb line.
16. Spike 10/10 at 60º – Spikes from lateral surface of model steel pile having length 10 cm and dia. 10 mm with their angle of inclination of 60º at a point w.r.t. positive direction of the vertical plumb line.
17. Spike 10/10 at 90º – Spikes from lateral surface of model steel pile having length 10 cm and dia. 10 mm with their angle of inclination of approximate 90º at a point w.r.t. positive direction of the vertical plumb line.
18. Spike 10/10 at exact 90º – Orthogonal spike from welded nut from lateral surface of model steel pile having length 10 cm and dia. 10 mm with their exact angle of inclination of 90º at a point w.r.t. positive direction of the vertical plumb line.
19. Spike 10/10 at 120º – Spikes from lateral surface of model steel pile having length 10 cm and dia. 10 mm with their angle of inclination of 120º at a point w.r.t. positive direction of the vertical plumb line.
20. Spike 10/10 at 150º – Spikes from lateral surface of model steel pile having length 10 cm and dia. 10 mm with their angle of inclination of 150º at a point w.r.t. positive direction of the vertical plumb line.

The main contribution of this work to the body of knowledge is introducing of invented special feature which resulted in increase in side resistance of a model steel pile and that, too, with almost slight disturbance to the soil while introducing a special feature.
In the entire history of pile literature, particularly in steel piles, special feature in the form of slotted holes (patented by; Kumar and Trivedi, 2013a, b) and spikes have not ever been invented and used so far to increase the side resistance of a plain steel pile including uniform tapered pile, stepped tapered pile, screw pile, helical pile, protruding welded hemi spherical balls distributed evenly on the entire lateral surface of the pile (a patented pile in U.S.A.) and lately, named a Fundex pile in which protruding vertical strips along the entire length of the pile spaced evenly diametrically and another, one an under-reamed pile, but definitely, a bored and augered reinforced caged concrete pile (not a steel pile). In all the above types of piles, increase in side resistance is minimal to a very low extent with respect to increase in side resistance in the presently explored specially featured (i.e. slotted-cum-spiked) pile. Also side resistance capacity is increased due to lateral effect of special feature in the form of slotted holes-cum-spikes on the entire lateral surface of the steel pile except its conical tip.

Uniform tapered pile increase, marginally, in load carrying capacity of a pile due to tapering effect of sloped surface along the length of the pile (Horvath, Trochalides, Burns and Margan 2004). Stepped tapered pile increase in end-bearing area leading to end-bearing resistance component of load carrying capacity of a pile (Hesham, Naggar and Wei, 1999). Screw pile, which not only it cuts the soil but it entirely, disturbs the natural fabric of the soil mass. Helical pile works the same way as in screw pile. Protruding welded hemi spherical balls distributed evenly on the entire lateral surface of the pile (patented in U.S.A.), while being driven deep inside into the ground, and disturbs the soil fabric. It cuts the soil and forms a space between the pile surface and soil interacting laterally along the entire length of the pile, which does not lead to much increase in side-resistance. An under reaming effect is not possible in the case of steel pile as it is for bored and augered reinforced caged concrete pile.

It is well known that side shear or “side resistance” of piles is known as skin friction whereas Terzaghi (1943) made a confessional statement that he did not not know much about “skin friction,” i.e. a side resistance. Of course, he had drawn a number of graphs based on earth pressure theories, but he apparently was not sure enough that those graphs were of practical value (Terzaghi 1943). Instead, he requested his friends and colleagues to perform site-specific load tests to measure side resistance; this remained a good advise for all of us even today since effects of construction, which are generally ignored in even the more sophisticated-cum-delicate design procedures, have a large effect on pile behaviour (O’Neill, 2001).

Years later, building on pioneering efforts by Seed and Reese (1955) and Vesic (1972) conceived and promoted the concept that the total and pore water stress fields in the soil surrounding a driven pile after installation could be estimated by invoking a theoretical model in which the soil is envisioned to act as if it were being thrust outward by an expanding cylindrical cavity. While the initial version of that theory has been improved upon and super-ceded, it was an excellent attempt to solve what Vesic referred to as one of the most difficult and vexing problems in all of engineering (Vesic 1977; O’Neill 2001).

Topics of side resistance of driven piles in saturated clay under monotonic loading, side resistance of piles in siliceous sand in uplift versus compression, side resistance of drilled shafts in clay and side resistance of drilled shafts in soft rock are of traditional interest that have received much attention from practitioners and researchers since the last series of Terzaghi lectures that exclusively addressed pile performance and design (McClelland,1974; Meyerhof,1976; Reese,1978). Research following that period of time has been motivated largely by the need to predict pile capacities accurately for offshore drilling platforms and to develop economical design methodologies for foundations of major highway bridges.

The computing pile resistances, even in the simple monotonic axial loading case, requires a keen knowledge of the effects of fundamental geotechnical and construction phenomenon and of the past performance of piles in geologic formations similar to that for which the pile is to be designed. While much is understood, much still remains to be learned, particularly concerning the effects of construction on the behaviour of individual pile pertaining to side resistance. These effects include such factors as the installation method (impact driving, jacking, vibrodriving, and rate of driving), lateral movements of piles during driving, and shear drag in layered soils in driven piles. They also include borehole roughness, water content of fluid concrete, time required for excavation (stress relief), impact of the details of drilling slurry, and the effect of drilling tools and practices on development of rock smear for side resistance.

The effects of construction procedures for pile groups, such as order and rapidity of pile installation (not discussed in this thesis) are equally important in the larger subject area of deep foundation systems. Inadequately quantified effects of construction lead to the inevitable conclusion reached by Terzaghi that site-specific load testing must remain an integral part of the design process for driven piles (O'Neill 2001).

Model steel piles were tested and their corresponding data was put into the form of tables. From the tables, corresponding load vs. settlements graphs were made. These graphs were made with a common scale for comparing the graphs and on different scales for individual graph. The literature on side resistance of steel piles was surveyed. The conclusion arrived in the present work agreed with other author's (Agerschou 1962, Flaate 1964, Olsen and Flaate 1967 and Sorensen and Hensen 1957 et al.) view point the that the oldest and most frequently used method of estimating the load capacity of driven pile i.e. by driving formulae or dynamic formulae (Poulos and Davis 1980) are unreliable (Agerschou 1962, Flaate 1964, Olsen and Flaate 1967 and Sorensen and Hensen 1957, et al.). Pile-driving formulae attempt to relate the dynamic to the static resistance of a single pile. They have been established on an empirical or a theoretical basis. Many of them are based on Newton's law of impact modified in some cases for energy losses impact and stress propagation.

All such formulae relate ultimate load capacity to pile set (i.e. the vertical movement per blow of the driving hammer) and assume that the driving resistance is equal to the load capacity of the pile under static loading (Poulos and Davis, 1980). These dynamic formulae were of course developed to overcome the deficiencies of static formulae (Poulos and Davis, 1980).

Smith (1960) stated that the editors of *Engineering News Record* had on file 450 such formulations. The derivation of some of these have been discussed by Whitaker (1970). Whole details of some of the required parameters are available in Chellis (1961).

The primary objective in using a pile-driving formula or static formula is usually either to establish a safe working load for a pile or to determine the driving requirements for a required working load. The working load is usually determined by applying a suitable factor of safety to the ultimate load calculated by the dynamic or static formula. This safety factor however, varies considerably depending on the dynamic or static formula used and the type of pile being driven. Also the static and dynamic formulae do not take into account of the nature of the soil, hence, the appropriate safety factor may varies from one site to another.

The conventional static load test has been believed to be the most reliable test method to obtain the load-settlement relation of a single pile (Matsumoto et al. 2007). However, to obtain a true load-settlement relation, in a static vertical load test, experimental set-up has been constructed in such a way that instead of taking reaction from reaction piles (influenced test piles), it comes from fixed support of steel girder fixed in walls to a true single pile(non-influenced test pile, Matsumoto et al. 2007) via a special arrangement of screw-jack technology converting compressive load into tensile load to determine side-resistance of medium scale model steel piles and large scale model steel piles. The above method comes under the category of pull-out side resistance to determine side resistance.

A detailed arrangement has been shown in a neat sketch under the sub-head entitled, “Construction of Field Laboratory” in Chapter III, “Experimental Programme”.

It is worthwhile to mention here that side resistance (discussed in this thesis) have been found out by pull-out resistance method for medium scale model steel piles and large scale model steel piles.

One such new construction technique is Pile Jacking Technology (White and Deeks2007) which has been used in the current research project. Due to limited manufacturing restraints, equipment had its static jacking force with a capacity up to 1000 kN. It has been discussed in detail in the present thesis under Chapter V, “Experimental Programme”. In the present work, a number of steel piles having different cross-sections and different special features have been fabricated at the lathe-machine.
The experimental data has been put in tables and relevant graphs showing load-settlement behaviour have been drawn.

It has been concluded that a model steel pile having special feature in the form of slotted holes (patented by author; Kumar and Trivedi, 2013a, b), with or without spikes had “ξ” (an improvement factor)times more side resistance than a simple plain model steel pile having no special features i.e. a plain model steel pile(henceforth, it will be called as a plain MSP). Similarly, a spiked-cum-slotted model steel pile has much more side-resistance than a simple pile having no special features (a plain MSP).
Also, it has been concluded that a doubly sloped circular side-finned model steel pile, having circular side-sloped fins provided at fixed intervals along the longitudinal length of the pile with its top surface contra-sloped inside gently and bottom surface sloped aggressively upwards outwardly, have significant more side-resistance than a simple plain model steel pile having no special features.

Quite interestingly, when the above doubly sloped circular side-finned model steel pile having slotted holes-cum-spikes, after insertion into the soil, was tested, then, side-resistance had been found to be increased significantly. Its increase was even more than either of a plain slotted holes model steel pile, plain slotted-cum-spiked model steel pile or doubly sloped circular side-finned model steel pile with slotted holes.

An improvement factor, ξ for all model steel piles have been mentioned in Chapter IV under the sub - heading on Analysis of Results.

The scope of future researches into the respective area has thoughtfully been provided under the heading of "Scope of Future Research"

6000 years ago, a neolithic tribe called the "Dwellers of Swiss Lake", who used to reside in what is now known as Switzerland. They have been credited with the conceptual thought of a pile for construction. These dwellers had used piling not for supporting construction loads as peoples do today, but for elevated heights to protect them from wildlife. (http://www.timberpilingcouncil.org/history.html).

In fact, the first historical document with a reference to piling can be traced back to the 4th century BC, which was documented by Herodotus, the Greek writer and traveller who was sometimes referred to as the father of history. His written records show clearly, how the Paeonians lived in dwellings erected on lofty piles driven into a lake bed (http://www.aeyates.co.uk/ tritech-piling-and-foundations-ltd).

The Romans had built many pile foundations for structures including building, homes, bridges, roads and viaducts and piles were their natural choice. The first bridge across the Tiber River in Rome on timber piles was built by the Romans in B.C. 1620. Piles were used for the foundations of Homes in the cities of Venice and Ravenna from B.C. 100 to A.D. 400. The first bridge across the Thames River in London was also built by the Romans in A.D. 60 on timber piling. Piles used for the Circus in Arles (France), built in A.D. 148 on wetlands, are still in excellent conditions and can be seen in the museum at the site.

The modern age of wood preserving began in England in 1832 with the concept of pressure injecting chemicals into wood. In the U.S. the first treating plant was built in 1848 for treating railroad ties.

The Erie Canal locks in New York, completed in 1825, were constructed with one- and two-ton blocks on the floor of the locks, supported on a system of 6-foot (1.8 meter) timber piles. Each lock was supported on 700 piles, arranged in rows of 15 to 20 piles across the width and two feet apart.

Piles are one of the oldest type of foundation system known to man and as such have been previously studied in depth based on available modelling and monitoring techniques. An increased understanding of piles behaviour coupled with the desire to develop cost effective foundations systems have resulted in a need to increase foundation efficiency. The increased knowledge of pile behaviour has been spurred by the development of improved analytical techniques, technological advances in monitoring instrumentation, a better understanding of installation effects and the distinction between group and single pile behaviour (Meyer, 1979, Young, et al 1984).

Before the development of modern analytical techniques, it was commonly believed that no rational relationship existed between the behaviours of single piles and pile groups. In his James Forrest lecture (1939), Terzaghi stated, "Both theoretical considerations and experience leave no doubt that there is no relation whatever between the settlement of an individual pile at a given load and that of a large group of piles having the same load per pile." Such statements quite properly encourage caution in dealing with pile groups that contain very large number of piles; these are often better considered as a large block foundation. However, for groups that contain relatively few piles, it is possible to link theoretically the settlements of single piles and pile groups.

The expansion of urban development into increasingly marginal sites, and the invention of new pile construction techniques, makes the economics of deep foundations increasingly attractive. Recent technological improvements have led to a proliferation of pile types and installation methods. Displacement piles, driven into the ground by hammering or vibration, remain widely used for offshore and near-shore foundations. For onshore foundations, non-displacement piles have increased in popularity during the past 56 years since these can be installed without the noise and vibration associated with conventional methods of pile driving (Deeks et al. 2005).

Increasingly stringent environmental legislation now precludes the use of pile hammers in urban areas, and restricts the disposal of spoil created by the construction of conventional bored piles. In response, alternative construction methods for pile foundations have evolved. These developments have been driven by a desire either to improve the performance of the foundation or to reduce the environmental impact of its construction. Performance is quantified by the strength and stiffness of the foundations. Noise, ground vibrations and spoil material (particularly from urban sites) all have negative environmental impacts (Deeks et al. 2005).

One such new construction technique is pile jacking, which is a subject of this project work. The Pile jacking has historically been used for the construction of small foundation piles, as are used for minor underpinning works. More recently, high capacity jacking machines have been developed, which offer the opportunity for the foundations of large buildings or heavy structures to be installed without the noise and vibration associated with conventional methods of displacement piling. Some pile jacking system can be supported on the pile wall under construction, rather than a piling mat, which reduces the need for temporary works leading to shorter construction schedules and reduced material use (Deeks et al. 2005).

For displacement piles, the installation method – jacking or dynamic driving – has an effect on the deformation of the soil during installation, and the resulting stress field around the pile. In turn, these factors affect the pile behaviour during subsequent loading. In design practice, the effect of installation method is rarely considered when assessing the response of a pile foundation. In some cases, design codes and research papers recommend empirical factors to differentiate between the capacity of bored and driven piles (e.g. Bustamanate and Gianeselli, 1982; De Beer, 1984; and 1988, and Ghionna et al. 1993, 1994) but as pile jacking is a relatively new technology little advice exists for predicting the behaviour of jacked piles. (Deeks et al. 2005).

Also, throughout the literature of pile study, from books to research journals, foundations have been categorised into shallow and deep. “Shallow foundations” (which is not a subject of this thesis) is referred to those structures which are supported by the soil lying immediately beneath the structure (Lambe and Whitman 1969). Deep foundations, referred to piles (which is a subject of this thesis), caissons or piers, are used to carry the loads to firm soils at some depth (Lambe and Whitman 1969).

Various types of piles are used for a variety of building structures and flyover bridges. The British Standard Code of Practice for Foundations (BS 8004: 1986) places piles in three categories. The three categories are as follows:

Large displacement piles comprise solid-sections piles or hollow-section piles with a closed end, which are driven or jacked into the ground and thus displaces the soil. All types of driven or jacked piles come into this category. (The steel pile with a hollow-section and closed at one end is a subject of my thesis).

Small displacement piles are also driven or jacked into the ground but have a small cross-sectional area. They include rolled steel H or I-sections and pipe section. Where these pile types plug with soil during driving they become large displacement piles.

Replacement piles are formed by first removing the soil by boring using a wide range of drilling techniques. Concrete may be placed into lined or unlined hole, or the lining may be withdrawn as the concrete is placed. Preformed elements of timber, concrete or steel may be placed in drilled holes. Continuous flight auger (CFA) piles have become the dominant type of pile in the UK for structures on land.

Euro code 7 (EC7) does not categorise piles, but Clause 7 applies to the design of all types of load-bearing piles. When piles are used to reduce settlement of a raft or spread foundation (Love 2003), as opposed to supporting the full load from a structure, then the provisions of EC7 may not apply directly. A basic classification with examples of displacement piles is given in BS EN 12699: 2000 (Execution of special geotechnical work-Displacement piles).

Types of piles in each of the BS: 8004 categories can be listed as follows:

Large displacement piles driven types:

Steel pipe pile close ended at base with a conical tip

The pile is composed of a steel pipe. Steel pipe pile types differ from each other according to the structure of the pile point, pile shaft and the pile driving method to be used. If a steel pipe pile is filled with concrete and adhesion between steel and concrete is sufficient, the structure can be assessed as a composite structure.

Unplugged open-ended steel pipe pile

This pile is a steel pipe, which is open at both ends and is driven into the ground with blows to the top of the pile. After the pile driving the ground level is approximately the same both inside and outside the pile.

Plugged open-ended steel pipe pile

This pile is a steel pipe, which is open at both ends and is driven into the ground with blows to the top of the pile. On completion of the pile driving the ground level is distinctly lower inside than outside the pile. The state of plugging of the pile is determined on the basis of the difference between the ground levels inside and outside the pile. Normally formation of the plug requires that the pile penetrates into the plugging soil layer not less than 10 x d length, where d is the diameter of the pile.

Steel pipe pile closed with bottom plate

This pile is composed of a steel pipe, which acts as a pile shaft, and a plate welded to the lower end of the steel pipe. This plate seals the lower end of the pipe. The pile is intended to penetrate into bearing soil layer. The pile is installed using a pile hammer, which delivers blows to the top of the pile, or by using a Franki pile hammer.

Steel pipe pile with rock shoe

This pile is composed of a steel pipe and a rock shoe welded to the lower end of the pipe. The function of the rock shoe is to transmit the pile load to the rock and prevent sliding of the point. The rock shoe should tolerate loading during the use of the structure and pile driving. The steel pipe pile with a rock shoe is driven with a pile hammer, which delivers blows to the top of the pile, or with a Franki pile hammer, which delivers blows to the lower end of the pile.

Franki pipe pile

The difference between a Franki pipe pile and a Franki pile is that in the Franki pipe pile the steel tube used as a working tube remains as a permanent structure.

Concrete pile with steel casing

The installation of the pile pipe requires no fulfilling of the settlement limits during the final set and the geotechnical bearing capacity of the pile is assessed according to the cast-in-place piles.

Review of Durability and Protection of Steel Piles from Corrosion

The corrosion studies are not a part of the present investigations. The present work has discussed about steel pile’s corrosion in the context of effectiveness of steel piles in the corrosion related aggressive environment.

Corrosion of iron or steel in the electrolyte provided by water or moist soil is an electro-chemical phenomenon in which some areas of the metal surface act as anodes and the other areas act as cathodes. Pitting occurs in anodic areas, with rust as the corrosion product air and water are normally essential to sustain corrosion but bacterial corrosion can take place in the absence of oxygen, i.e. in anaerobic conditions. Anaerobic corrosion is caused by the action of sulphate-reducing bacteria which thrive below the sea or river bed in polluted waters, particularly in relatively impermeable silts and clays.

An exhaustive investigation of the corrosion rates of steel sheet piles and bearing piles in soils was made by Romanoff (1962, 1969), on behalf of the US National Bureau of Standards. Steel piles which had been in the ground for periods of between 7 and 40 years were examined. The soil types ranged from permeable sands to relatively impervious clays. Soil resistivity ranged between 300 and 50200 ohm-cm and pH values between 2.3 and 8.6. Romanoff concluded from observations of the condition of the piles that where they were driven into undisturbed natural soil, the type and amount of corrosion was so small that it would not significantly affect the strength or useful life of the piling to support structures. Some localized pitting corrosion and loss of mill-scale were seen on steel surfaces but the loss of metal was considered to have a negligible effect on the serviceability of the steel piles. Corrosion had occurred in some instances where piles had been driven through fill above the water table, or in the zone extending 0.6 meter above and below the water table.

Romanoff (1962, 1969) pointed out that undisturbed natural soils are so deficient in oxygen that they will not sustain the process of corrosion. Romanoff (1962, 1969) also found that determination of soil resistivity and pH-value had no relevance to the incidence of corrosion in the undisturbed soil conditions covered by the Bureau of Standards research. He did not encounter any cases of anaerobic corrosion by sulphate-reducing bacteria but the possibility of their occurrence should not be overlooked at the site investigation stage. Undisturbed samples of the soil should be sealed in their containers and submitted for bacteriological examination.

In a later study, Romanoff (1969) examined steel sheet piles which had been driven through fill material. Inspections were made at 13 locations where piles had been installed for periods of between 11 and 30 years. With only one exception the piles showed only shallow attack on the metal with some localized pitting corrosion. The single exception was at a site where sheet piles had been driven through 6 m of clinker filing. Severe attack on the metal and pitting up to 6 mm deep had occurred over large areas. However, it was pointed out that these piles were continuing to give useful service 23 years after they had been driven. Romanoff concluded that the relatively small amount of corrosion over the portion of the pile in fill or in undisturbed soil above the water table is the result of the formation of a galvanic corrosion cell between the upper part of the pile above the water table and the lower permanently immersed part. The upper portion is small in volume compared with the lower portion and it acts as a cathode, while the lower part in soil deficient in oxygen is the anode. Because of the much greater mass of steel in the anodic portion only a small proportion is sacrificed in protecting the catholic part.

Similar corrosion rates for piling in land structures have been recorded by Morley (1979). British Steel Corporation investigation of piles extracted from UK sites (Morley 1970) showed corrosion losses below the soil line varying from nothing to 0.03 mm per year with a mean of 0.01 mm per year. No precautions are required for such low rates of loss of thickness. Where piles in land structures are extended above ground, mild steel thickness losses of 0.2 mm per year were measured over a 10-year period in a marine environment. Morley considered that a more usual figure for UK would be 0.1 mm per year. For steel bearing piles in natural soils, BS 8002 and BS 2004 advised a maximum corrosion allowance of 0.015 mm per year per side where no other corrosion protection is required; this is consistent with corrosion rates derived from Euro code EC3-5 (Piling). The long –term corrosion rate of piles in normal atmospheres in urban conditions given in EC3-5 is 0.01 mm per year per side and for coastal areas 0.02 mm per side per year. In areas where localized conditions give rise to more aggressive microclimates the greater allowances in BS 8004 may be needed. Paint treatment, as specified in, "A corrosion protection guide – For steelwork exposed to atmospheric environments published by Corus construction and Industrial, Scunthorpe, 2004" would be a suitable precautionary measure for the exposed steel provided that it is accessible for maintenance. If the aesthetic appearance of the steel is important, then the, "Piling Handbook, Arcelor RPS, Luxembourg and Scunthorpe (2005)" suggest application of coating systems using zinc silicate epoxy primer and aliphatic polyurethane topcoat. Where the water table is shallow the pile cap can be extended down to a depth of 0.6 meter below water level to protect the steel of the piles.

Morley (1979) reported a corrosion rate of 0.05 mm per year for steel piling immersed in fresh water except at the waterline in canals where the rate was as high as 0.34 mm per year. This locally higher corrosion zone may be due to abrasion by floating debris or to cell action between parts of the structure in different conditions of oxygen availability.

The pH range of fresh water has little effect on corrosion, but to reflect the variability due to potential pollution, the corrosion rate allowances derived from EC3-5 are approximately 0.02 to 0.05 mm per year per side. Corus (2005) suggested in his, “corrosion protection guide for steel bearing piles in temperate climates” that glass flake epoxy coating with nominal dry film thickness of 400 micron meter be used for piers and jetties to extend the time to the first maintenance period to beyond 20 years. An alternative for shorter maintenance periods, in both immersed and atmospheric exposures, is a polyamine-cured epoxy with dry film thickness of 300 micron meter (Corus 2005). The coatings must be applied over blast-cleaned steel. Isocynate-cured pitch epoxy and cheap coal tar coatings are no longer recommended and are being phased out for health and safety reasons. Paint coatings are not generally satisfactory for protection against bacterial corrosion. Any pinholes in the coating or areas removed by abrasion serve as points of attack by the organisms. Cathodic protection is effective but higher current densities are required than those needed to combat normal corrosion in aerobic conditions.

Where steel piles are buried in fill or disturbed natural soil, the thickness of metal in a bearing pile should be such that the steel section will not be over stressed due to wastage of the metal by corrosion over the period of useful life of the structure. Taking a figure of 0.08 mm per year as a maximum in the range established by the US Bureau of Standards for disturbed ground, a steel H-pile with web and flange thickness of 15.5 mm exposed to the soil on both sides will lose 50% of its thickness in a period of 48 years, although there may be localized areas of deeper pitting. Long –term corrosion allowances for service periods up to 100 years provided in EC3-5 for non-aggressive and aggressive non-compacted fills are approximately 0.02 mm per year per side and 0.06 mm per year per side respectively. In compacted fills these figures may be halved. Marsh and Chao (2004) have refined the contamination guidelines so that more accurate long-term corrosion allowances can be made. Protection coating of piles in severely contaminated ground should resist abrasion, impact, and acidic attack. Using a polyamide-cured epoxy system with increased chemical resistance and a nominal dry film thickness of 480 micron meter onto blast-cleaned surfaces. Protection should extend to around 0.6 meter below water table.

Other protective measures in contaminated disturbed ground include jacketing the pile with concrete or filling the shafts of hollow piles with concrete capable of carrying the full load.

Corrosion Studies

If steel pipe piles are used, the potential corrosion risk has to be investigated.

Steel Pipe Piles–Soil Survey

The degree of aggressively of the natural and homogeneous soil is normally minimal. Notable corrosion may occur only in aerobic conditions. Aerobic conditions occur above the lowest design groundwater level. The aggressiveness of the soil must be investigated with corrosion measurements if there is organic soil, fillings, or sulphur clay in the area, or if water surrounding the pile is contaminated. Especially aggressive can be such soils, which have a low specific resistivity and pH-value. Several factors affect the soil corrosion thus making the joint effect difficult to estimate. Corrosion investigations can examine the effect of one, individual factor. The most important factors are the moisture content, the amount of organic material, the acidity, and the specific resistivity, the chemical composition of the pore water as well as the location and variation of the ground water level. The specific resistivity is determined in the field using Wenner's four electrode method or a rod electrode. In the laboratory, the specific resistivity can be determined using the soil box method or the insertion electrode method. Various corrosion probes can also be used in corrosion investigation or applicable electrochemical measurements can be performed. During the soil survey, extra soil samples should be obtained to facilitate laboratory corrosion investigations. With regard to the handling and storing of samples, special care should be taken to prevent disturbance and oxidation. Laboratory tests should be carried out as soon as possible to avoid altering of the properties of the samples. Electricity plants, power lines and electric rail traffic in the vicinity of the building site may cause stray current corrosion, the amplitude of which can be evaluated by measuring the leakage current and conductivity of the ground.

Precautions for the changes in the corrosion environment during the planned working time of the piles must be taken, if necessary, by reserving the protected area or other measures available for the builder. In soils containing sulphur, i.e. sulphide clays, microbiological corrosion may occur in anaerobic conditions. Microbiological corrosion can be evaluated by investigating the quantity of species and the activity of the microbes in the soil. Sulphide clays may appear in an area of Litorina clays and occasionally in Ancylus clays. On the basis of the corrosion investigations an appropriate corrosion protection method is selected.

The major application for stainless steel in soils is in the form of tubes and pipes for the transportation of different liquids such as chemicals, water or sludge. Another example of use of stainless steel is for foundation pillars instead of carbon steel pillars. The limiting factor for usage of stainless steel in soils is often considered to be related to cost or corrosion problems. There are, however, suitable stainless steel grades for every application in different types of soil and their superior properties make them an excellent choice of material.

Corrosivity of Soils

There are several factors that contribute to the corrosivity of a soil, namely

- Type of soil
- Resistivity
- Chloride and Sulphate content
- Aeration
- pH
- Presence of stray currents

The characteristic of the soil itself in terms of particle size affects the drainage of water. An electrolyte is always needed for electrochemical reactions to occur. Therefore, a moist environment often contributes more to corrosion attack than a dry environment due to the accumulation of water and dissolved salts. The most corrosive soils are clays, silts and loams (Cunat, 2001). Sands and gravel exhibit a wide range of particle sizes but have generally a good drainage and therefore high resistivity and low corrosivity.

There are many factors affecting the corrosivity of the soil but the resistivity appears to be one of the factors that best describe the relationship between soil properties and corrosivity. The resistivity is decreased as the concentration of dissolved salts and ionic species is increased. A more conducting electrolyte results in higher corrosivity than are exhibited by a soil with higher resistivity. Different authors denote nominal resistivity values corresponding to certain corrosivities differently. However, a resistivity below 3000 ohm-cm indicates a corrosive soil according to the EN 12501-2 standard (SS-EN 12501-2, 2003).

The effect of chlorides is twofold. The Chlorides lower the resistivity and participate in the breakdown of the protective passive film on the stainless steel surface, resulting in the initiation of localized corrosion. The presence of chlorides is naturally higher in brackish and salt water but can also be the result of human activities such as de-icing of roads. The Sulphates may initiate corrosion attack but are generally considered as less aggressive. However, the sulphur might be reduced by bacteria under anaerobic conditions, resulting in sulphides that can attack the stainless steel. These bacteria flourish at normal pH, room temperature and in clays, silts and loams (Cunat, 2001).

The aeration of soils is complex. Oxygen is needed for the cathodic reaction component of the corrosion reaction. High oxygen concentration increase the thermodynamic driving force, which often leads to an increased corrosion rate. A low concentration of oxygen might be disadvantageous because it facilitates the growth of anaerobic bacteria. However, dense clays with a very low aeration rate and no microbial activities will practically be non-corrosive when the oxygen has been depleted (Cunat, 2001).

The pH value is of great importance when it comes to soil corrosivity. However, stainless steels are not as sensitive as other materials: the pH of ordinary soils is often of no concern. Environments with pH < 5 start to be corrosive to the stainless steel in chloride-containing soils.

Side-Resistance in the Context of Load Holding Capacity of a Steel Pile

With the familiarity of the fact that the friction coefficient is just a convenience, describing a friction system and not a materials property.

Dr. Ing. Geert Salomon (1964).

Dr. Ing. Geert Salomon(1964) reported that there is still much to learn about the nature of friction, how it changes under different circumstances, and how it can be predicted and controlled. Its effects on the behavior of machines and materials have been the source of study and contemplation for hundreds and even thousands of years, reaching back at least as far as Aristotle (384-322 B. C.) Great thinkers like Hero, da Vinci, Hooke, Newton, Euler, and Coulomb, all considered friction; yet a complete description of its fundamental causes and a single quantitative model- which is generally applicable to any frictional situation- has yet to emerge (Gemant’s book, “Frictional phenomena” Revised second edition October 4, 1950).

There are many manifestations of friction. Gemant’s book, “Frictional phenomena” (Revised second edition, October 4, 1950) describes a host of phenomena all related to friction. He stated, with remarkable foresight, over 64 years ago, “Indeed, it is hard to imagine any process, whether in nature or in industry, that is entirely free of friction. It appears that only processes of the largest and the smallest dimensions, namely astronomical and inter-atomic motions, can be described without the involvement of friction. However, even this situation might change with a better understanding of the universe on the one hand and of the elementary particles in the atom on the other.”

Problem Definition

Side resistance of a pile comes from facial interaction of lateral surface of a pile and the soil surrounding the soil-mass. In steel pile, it is the plain lateral surface. Can this side resistance be increased by providing any means of special feature, thereby, reducing the length of a special featured pile and hence economizing the foundation cost?

Problem Solved by the Invention

Side resistance of a pile in the soft soils can be very low for a few days after driving, and the effect of pore pressures caused by driving adjacent piles in the group may cause the piles already driven to rise out of the ground due to their own buoyancy relative to that of the soil. (Tomlinson and Woodward 2008).

This is one of the problems, whenever the piles are driven into the soft soils. A combination of Spikes and naked mesh-filtered or naked mesh-plugged slotted holes (an invention patented by author) on the modal steel pile has solved this problem.

Mechanism Involved in Solving the Problem

Driving a closed ended steel pile inside the soil mass leads to immediate build-up of pore water pressure in the voids of surrounded soil-mass around the lateral peripheral surface of a modal steel pile due to induced lateral compressive stress. This immediate build-up of pore water pressure in the voids of soil mass leads to reduction in side-resistance at soil-steel pile surface interaction, thereby, reducing the immediate load carrying capacity of a steel pile as well as more settlement of a steel pile for a unit load acting on top of the steel pile. It also reduces the coefficient of side–resistance i.e. the load carried by unit lateral surface area of a modal steel pile.

Now, due to development of pore water pressure, water from voids of laterally compressed soil mass flows away from steel pile surface towards a point of least distance having lower pressure, through the adjacent voids of soil-mass. Ground surface, always at being lower water pressure potential than the point at compressed soil-mass near the steel pile surface, that, too, all along the depth of a steel pile, happens to be more attractive for water molecules under pressure to travel towards it. In due course of flow action towards the ground surface, of course radially also, flow action forces the adjacent piles in the group, already driven, to rise out of the ground due to their own buoyancy relative to that of the soil.

The water molecules under pressure are provided an immediate and easy escape through the mesh-filtered or mesh-plugged slotted holes, provided throughout on the lateral surface of the steel pile (an invention patented by author), then, the pore water pressure would fall down to its original level in the minimal time. Of course, the accumulated water at the base of conical tip of steel pile, will be removed automatically by, a hydraulic pump fitted with an electronic sensor to judge top water level inside the steel pile, through a stainless steel pipe having its outlet end out of the slotted hole at top end of a slotted steel pile. Its immediate effect would be increase of effective stress in the surrounded soil–mass due to increased total lateral radial consolidation compression of soil mass. As, Terzaghi (1943), had said, "Increase in effective stress is directly proportional to increase in shear strength of soil-mass". This increase in shear strength of radially consolidated soil-mass leads to more side-resistance at the pile-soil interaction due to increased skin-frictional resistance. Not only side-resistance at the pile-soil interaction increases the load carrying capacity (its other name is load holding capacity as coined by Sobolevsky, 1995), but also the bearing strength of the soil-mass.

In the next step, corrosion resistant stainless steel spikes oozing, orthogonally, out of slotted holes (an invention patented by author) are provided on the lateral surface of the steel pile. These spikes acts like an interlocking arrangement between the surrounded consolidated soil-mass and the lateral surface of the steel pile. These spikes, acts like reinforcing bars makes the surrounded consolidated soil-mass equivalent to a reinforced earth. This reinforced earth together with spikes interlocks the steel pile surface with the reinforced consolidated soil-mass. This, spiked interlocking, in turn, increases the side resistance of the steel pile enormously.

Not only these spikes reinforce the surrounded consolidated soil-mass, but half of their peripheral surface acts as an end bearing area, which in turn in either way in tensile or compressive load carrying capacity gives a certain increase in side resistance. The most important benefit of this invention is that the side resistance provided by a combination of left-over naked holes and spikes increases the side-resistance of steel pile tremendously. Similarly, the torque resistance provided by the spikes and the consolidated soil-mass surrounding the model steel pile is increased by a huge amount. But, in all the slotted model steel piles, spiked model steel piles, slotted-cum-spiked steel pile and doubly sloped circular side finned wall with slotted and spike-cum-slotted model steel pile, had been fabricated and tested without mesh-filter and without mesh-plugs.

A careful and cautious approach for an experimental programme consisting of experimental studies was made. Till date, there has been insignificant record of experimental testing on model steel piles, with the pile diameter greater than or equal to 22.8 cm in the entire literature of pile testing on steel piles. Of course, some work has been reported on pencil steel piles for study of torque resistance decided upon (Kong and Jones, 2006).

First of all, size and scale of the model steel piles was chosen. The steel piles on large scale were fabricated. A number of photographs have been depicted in this chapter as well as a chapter on "Testing of Model steel piles".

A number of varied steel pile sections were fabricated at lathe machine.
Twenty six experimental tests were conducted on various sizes and scales of model steel piles. First test was conducted on plain model steel pile (Drawing 1, Table 4 and Fig.5). Second test was conducted on slotted model steel pile (Drawing 2, Table 5 and Fig.6). Third test was conducted with welded nuts slotted holes model steel pile (Drawing 3, Table 6 and Fig.7). Fourth test was conducted with spikes of length 2.0 cm and dia.10 mm through slotted holes on model steel pile at 90° (Drawing 4, Table 7 and Fig.8), fifth test was conducted with spikes of length 4.0 cm and dia.10 mm through slotted holes on model steel pile at 90° (Drawing 5, Table 8 and Fig.9), sixth test was conducted with spikes of length 6.0 cm and dia.10 mm through slotted holes on model steel pile at90° (Drawing 6, Table 9 and Fig.10), seventh test was conducted with spikes of length 8.0 cm and dia.10 mm through slotted holes on model steel pile at 90° (Drawing 7, Table 10 and Fig.11) and eighth test was conducted with spikes of length 10.0 cm and dia.10 mm through slotted holes on model steel pile at 90° (Drawing 8, Table 11 and Fig.12). Ninth test was conducted with spikes of length 2.0 cm and dia.8 mm through slotted holes on model steel pile at 90° (Drawing 9, Table 12 and Fig.13) , tenth test was conducted with spikes of length 4.0 cm and dia. 8 mm through slotted holes on model steel pile at 90°

(Drawing 10, Table 13 and Fig.14), eleventh test was conducted with spikes of length 6.0 cm and dia.8 mm through slotted holes on model steel pile at 90° (Drawing 11, Table 14 and Fig.15), twelfth test was conducted with spikes of length 8.0 cm and dia. 8 mm through slotted holes on model steel pile at 90° (Drawing 12, Table 15 and Fig.16) and thirteenth test was conducted with spikes of length 10.0 cm and dia. 8 mm through slotted holes on model steel pile at 90° (Drawing 13, Table 16 and Fig.17). Fourteenth test was conducted on model steel pile having slotted holes-cum-inclined spikes of length 10.0 cm and dia. 10 mm at 30° inclination at a point w.r.t. positive direction of vertical plumb line (Drawing 14, Table 17 and Fig.18). Fifteenth test was conducted on model steel pile having slotted holes-cum-inclined spikes of length 10.0 cm and dia. 10 mm at 60° inclination at a point w.r.t. positive direction of vertical plumb line (Drawing 15, Table 18 and Fig.19). Sixteenth test was conducted on model steel pile having slotted holes-cum-inclined spikes of length 10.0 cm and dia. 10 mm at 90° inclination at a point w.r.t. positive direction of vertical plumb line (Drawing 16, Table 19 and Fig.20). Seventeenth test was conducted on model steel pile having slotted holes-cum-inclined spikes of length 10.0 cm and dia. 10 mm at 120° inclination at a point w.r.t. positive direction of vertical plumb line (Drawing 17, Table 20 and Fig.21). Eighteenth test was conducted on model steel pile having slotted holes-cum-inclined spikes of length 10.0 cm and dia. 10 mm at 150° inclination at a point w.r.t. positive direction of vertical plumb line (Drawing 18, Table 21 and Fig.22). Nineteenth test was conducted on model steel pile having slotted holes-cum-inclined spikes of length 10.0 cm and dia. 10 mm at exactly 90° inclination at a point w.r.t. positive direction of vertical plumb line (Drawing 19, Table 22 and Fig.23). Twentieth test was conducted on model steel pile having doubly sloped circular finned (faced vertically upwards) steel pile with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals. Dry sand was not added manually in between the fins while the steel pile is being driven inside the dry sand (Drawing 20, Table 23 and Fig.24). Twenty-first test was conducted on model steel pile having doubly sloped circular finned (faced vertically upwards) steel pile with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals (Drawing 21, Table 24 and Fig.25). Similarly, twenty-second test was conducted on slotted holes doubly sloped circular finned faced vertically upwards with manual addition of dry sand in between the fins (Drawing 22, Table 25 and Fig.26). Similarly, twenty-third test was conducted on welded nuts slotted holes doubly sloped circular finned faced vertically upwards with manual addition of dry sand in between the fins (Drawing 23, Table 26 and Fig.27). Similarly, twenty-fourth, twenty-fifth and twenty-sixth test were conducted on spiked-cum-welded nuts slotted holes doubly sloped circular finned with its fins facing vertically upwards, corresponding to outward spiked out length of spikes of 10 mm dia. from the lateral surface of the model steel pile were 6 cm, 8 cm and 10 cm respectively (Drawing 24, 25 and 26, Table 27, 28 and 29, Fig.28, 29 and 30 respectively). Experimental tests with spikes of 2 cm and 4 cm were not conducted because the length of spike was lesser than the width of outward flange width of 5 cm and were unable to ooze out from the outer boundary of fins.

The five tests with inclined spikes were conducted for different ranges of inclination of spikes. The spike inclination, "β^{o}" w. r. t. vertical plumb line is defined as any angle at a point on a model steel pile between outside upward plain surface of a model steel pile and inclined spike and varies in the range $0^{o}<\beta^{o}<180^{o}$ for the vertical direction at specified constant angular intervals of 30^{o} (where $\beta^{o}=30^{o}$, 60^{o}, 90^{o}, 120^{o} and 150^{o} were considered in increasing order in the clockwise direction when spikes were to be seen on the right of the vertical axis of upright direction of the model steel pile. In the present thesis β^{o} could not be equal to 0^{o} or 180^{o} i.e. spikes in the case of pull-out of model steel pile could not be erected vertically upwards or vertically downwards through the slotted holes).

Also, out of the twenty-six tests, seven tests were conducted on doubly sloped circular finned slotted-cum-spiked pile. As for all the tests, diameter of model steel pile was kept the same.

The same numbers of seven model steel piles were fabricated with a special feature (a part of a special feature has been patented by Kumar and Trivedi 2013a, 2013b, 2014a, 2014b and 2015). These model steel piles were fabricated with slotted holes all over its lateral surface provided in a regular pattern of horizontal and vertical spacing. The plain spikes having different cross-sectional areas were fabricated at lathe machine shop of Samaipur Badli industrial area, Delhi-110042. The plain spikes having different length and different diameters were fabricated. These spikes were used for model steel piles in different experiments via spike holder or welded nut method put at different inclinations.

During experiments with the plain spikes, a site-specific difficult problem of maintaining orthogonality as well as fixed inclined direction of the plain spikes from slotted hole of lateral surface of a model steel pile had been adopted.

The peculiar problem was a real- time problem of getting the spikes, out from slotted hole, in an orthogonal as well as inclined direction in an outward direction from the lateral surface of a model steel pile and that, too, in an undisturbed surrounded soil-mass of already jacked steel pile. It was got implemented at a lathe machine of a very experienced mechanic and later patented (Kumar and Trivedi, 2013a, 2013b, 2014a, 2014b, 2015).

By the above process of inclining of spikes through a spike holder, one can transform the compressive load bearing steel pile to a tension load bearing steel pile for resisting upward forces.

A combination of spikes (A subject matter not discussed in this thesis) can also be designed to make the model steel pile equally effective for compressive as well as tensile load. Even the same steel pile can resist both the compression forces as well as tensile forces by giving desired inclination to the required number of spikes through a spike holder, which was welded behind the slotted hole.

More side resistance can be achieved by increasing roughness on the lateral surface of steel pile. The surface roughness can be increased either by indentations on lateral surface or by especially art-crafted design procedure or the surface of plain spikes was made rough by changing over to threaded one.

A number of model steel piles were fabricated with a special feature. Details of model steel piles have been described in Chapter IV: Experimental Data, Analysis, Results and Discussions under the sub-title of, "Experimental Results of Model Steel Piles". In designing a pile, one has to consider not only the structural capacity of the pile, as for as the support from the soil for load transfer, is concerned, but, also the strength of the bracket connection at the base of the spike i.e. "spike-holder". Real time testing of pile not only checks up its load holding capacity, but, also its own inherent strength. (Lambe and Whitman, 1969).

Next challenge was selection of thickness of a model steel pile. After initial checking tests on steel piles w.r.t. twisting and deformed ends of capped end of steel pile, it was concluded, for its structural strength, to provide 3mm thickness of steel piles for final testing.

Some of the photographs of model steel piles have been shown in the chapter III: "Experimental Programme" under the sub-head title of, "Fabrication of Model Steel Piles: Photograph Gallery".

Their detailed drawings have been shown in the chapter IV: "Experimental Data, Analysis, Results and Discussions of Model Steel Piles".

Construction of Field Laboratory

Fabrication of Apparatus

The experimental setup for carrying out the pile pull out test has been constructed in a number of stages:

Construction of Pit for Experiment

The first step was the construction of pit where the experiments were to be conducted. Various options namely like using an open container, cylindrical tanks were considered but none of them could replicate as well as simulate the field conditions. So, it was decided to construct an open pit using bricks and cement mortar. The dimensions of the first experimental pit were kept 2.75 m x 1.83 m x 2.0 m. The size of the pit was chosen because the construction site was already surrounded by brick walls. The surrounding walls were of 23 cm thickness.

Next to the construction of pit, a reaction unit was fabricated and erected above the pit. Its details have been given under the chapter III: "Experimental Programme" under the sub-head title of, "Construction, Erection and Fabrication of Reaction Unit".

In the first experimental pit, two compartments of size 1.375m x 1.83m x 2.0 m were made. In the first compartment, rocky fragments, consisting of coarse aggregates of average nominal size 50 mm and in the other compartment, crushed stone aggregates of average nominal size 11 mm were used.

Photograph 1: First Experimental Pit.

Photograph 2: Erection assembly being lifted up.

As the model steel pile of diameter 10 cm and length 1.0 m, was hammered to drive into the rocky fragments consisting of coarse aggregates of average nominal size 50 mm, the model steel pile could not drive inside the fill. Instead, the pile cap was deformed at its top end. In the second experiment with coarse aggregates of size 11 mm, similar, fate was met. Not only the model steel pile was completely damaged at its top end, but also it led to collapse twice due to side way tilt with the impact force of the hammer while being driven.

Therefore, it was imperative to make the model steel pile structurally strong, alternatively, the soil mass in the laboratory to be a soft one to be penetrated at a small load and that, too, at small incremental rate. The first option was used by strengthening a flange plate near the top of model steel pile by an electric arc welding. On testing drive of same welded model steel pile, one end of the reaction unit started yielding. Further, it was difficult because of insufficient generation of reaction load from an already fabricated reaction unit. Hence, the first experimental unit was fully dismantled.

So, the drawing preparation for the second experimental pit began. Then, a reaction unit was refabricated and re-erected in properly aligned direction. Hence, as a second choice the dry sand was to be placed into the pit. Next was the issue of maintaining and measuring the relative density of dry sand in-situ at the experimental pit.

The density in the pit was uniformly maintained by a free-fall of dry sand from a height of one meter while the dry sand was being put into the experimental pit in a properly distributed manner.

During the next experiment, dry Yamuna sand (here in after called as dry sand) was used. This dry sand was not brought directly at the laboratory site. It was obtained by sun-drying of partially saturated sand in the peak of summer season namely the month of May and June. It was spread evenly on a concrete surface to an average thickness of 10 cm. After every two hours, the sand was made to dry in such a way that almost the entire top surface of sand went upside down and vice-versa. The process was repeated three times at the interval of two hours in a total of eight hours during sunshine. The process was repeated over the period of three days. In the evening, it was collected at one place after dry sieving and put back into the experimental pit from a calculated and maintained height of one meter, every time, as per relationship of relative density and free falling height of dry Yamuna sand. This relationship was established prior to the construction of pit and its brief details have been discussed in the preceding paragraph. The process of putting back the dry sand into an experimental pit was made in such a way that, it was made to fall through an iron sieve of external size 50 cm x 50 cm from a height of one meter. This iron sieve had its sieve size just enough to let the sand pass through and have a free fall. A constant relative density was maintained uniformly throughout the entire sand mass, being one of the important parameter. This process was repeated till the experimental pit was full up to its top brim level.

A grain size distribution of dry Yamuna sand was obtained by a dry sieve analysis. A particle size gradation curve was made in a semi log plot in Fig. 2 and Fig. 3 in the

Chapter III: “Experimental Programme” under the sub-head title of, “Fill Material Characteristics”.

Next, material for steel pile was chosen in a form of steel sheet varying from 2 mm to 3 mm. As per the earlier experience during testing of model steel piles in coarse aggregates, where the top pile cap end of model steel piles were being deformed, the model steel pile thickness was structurally revised from 2 mm to 3 mm. Steel sheets of 3 mm were cut, moulded, fabricated, welded and grinded to a finished shape, as per drawing drawn in advance, in such a way at the lathe machine by a fabricator mechanic, that, the final manufactured piece was a model steel pile of desired length, desired cross-sectional dimensions and desired special features and that too with structurally strengthened top end of a model steel pile cap. In all, a number of piles, corresponding to twenty-six tests were fabricated as per chapter III: “Experimental Programme” under the sub-head title of, “Fabrication of Model Steel Piles: Photograph Gallery”.

As the experience of the earlier experimental pit was not satisfactory w.r.t. driven model steel piles in the coarse aggregates, so, the dry sand had been chosen as he next fill for the new pit. During testing it was found that even the brick walls had started cracking. One notable point here was that the top end of new model steel pile did not get deform. But, it had changed the view point of the author that the experimental pit should not only be structurally strong enough i.e. yield proof, but, should also be able to bear strong lateral earth pressure.

There was a need to have third field laboratory, where all the model steel piles having a special feature could be tested and that, too, without fail from structural point of view of model steel pile as well as of retaining brick wall of an experimental pit. A third experimental pit was to be constructed for conducting testing on modal steel piles.

So, a third construction site was erected at the site of first experimental pit. where it had existed. The clear visible open space was bounded by already constructed one room wall thickness 23 cm on left side (being a part of room), another wall of thickness 23 cm on the right side and the third wall of thickness 23 cm was at its back(being a part of lobby wall in its background). The front wall was a retaining wall having its base width 1.0 m and top wall thickness 23cm. Front retaining wall face was made a stepped one so that one could enter into the laboratory without any difficulty. The specific chosen site was having its artificially raised ground level above the natural ground level. An experimental site bottom ground level, after finishing stage, was kept to a depth of 1.5 meter.

First of all, an engineering drawing was made for constructing a third experimental pit, showing all the dimensions length, breadth and height. The dimensions of the third experimental pit were almost doubled from the previous one. It had been constructed for conducting experiments on model steel piles having a special feature. The dimensions of the second experimental pit were kept 2.75 m x 3.65 m x 3.5 m. The size was chosen so that the field conditions could be simulated as for as possible. To maintain specific depth, soil at existing located site was excavated up to 1.85 metre and then at a certain excavated level, the coarse aggregate of size 50mm to 70 mm was poured and it was compacted well with a manual rammer by sprinkling some water all over its surface. Finally, the compacted thickness of the bottom layer was 20 cm. A cement concrete of ratio 1:1.5:3 was laid all over the already compacted bottom layer, to a thickness of 15 cm. It was cured for 14 days. At a distance of 3.65 metre from inner face of back wall of the experimental pit, a front retaining brick wall of 2.75 metre long was constructed. It had its inner face vertical and front outer face a stepped one. The stepped face has a rise of 30 cm and tread of 5 cm was constructed in the form of a retaining wall with top thickness 23 cm and bottom thickness one metre (See under sub-title of photograph gallery of Chapter III, “Experimental Programme). Height of the brick wall above the existed ground level was 2.0 metre. The final depth of the pit was achieved at 3.5 metre i.e. 2.0 metre (above the existing ground level) and 1.5 metres (below the existing ground level).

Finally, an experimental pit of internal dimensions 2.75m x 3.65m x 3.5m was constructed. Top of front retaining wall was cement plastered to a thickness of 20 mm.

Then, the brick wall faces were cured fully by sprinkling water all over the brick masonry surface. Its inner surfaces were smoothened by cement plaster (Cement mortar of ratio 1:3). Then, a pit was fully cured for a period of 14 days. And, then, it was dried for another one month during the summer season. Once, the pit was fully dried, a transparent shed (monsoon rain-proof) was laid all over it as a sloped roof at a height of 3.5 metre above the top of experimental pit and at 1 m above the top of steel girder.

The process of putting the sand in the third experimental pit was repeated as was done for second experimental pit and has been explained thoroughly during filling of sand in second experimental pit.
It was spread all over the concrete surface of concrete road to get it fully sun-dried having almost negligible moisture content. Then it was sieved for any vegetation or stone pebbles.

After drying the sand, it was put into the experimental pit from a height of 1.0 metres so that the sand can remain in its medium loose state having a constant relative density. It was done in order to maintain, a constant relative density uniformly throughout the entire sand mass, being one of the constant parameter. This process was repeated till the experimental pit was full up to its top level i.e. in this case it is top level of front retaining brick wall.

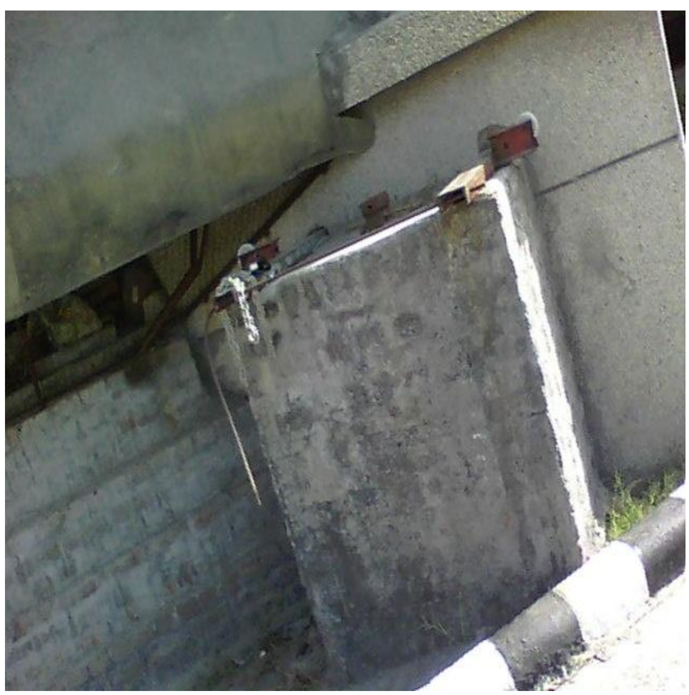
Construction, Erection and Fabrication of Reaction Unit

An I-shaped steel cross-section was selected, and was used as a plate girder. It was raised to a height of 3.5 metres above the top level of sand filled in the pit of field- lab and its ends were fixed into the opposite walls. This reaction girder has been used for applying reaction loads on to the top of capped model steel piles. The reaction load` from the steel girder was taken by applying pressure from hydraulic- jack, which was kept on top of steel pile**.** (See Photographs 3, 4, 5 and 6).

Photograph 3: Erection arrangement for verticality.

Photograph 4: Fabrication of plate girder – pulley.

Photograph 5: Construction of Shed along with stepped brick retaining wall.
Photograph 6: Second Pull-out pit for Steel Piles



Fabrication of Model Steel Piles: Photograph Gallery

The model steel piles as per chapter VII: Testing of Model Steel Piles, under the sub-title, "Drawings, Tables and Figures" of sub-head, "Experimental Results of Model Steel Piles" were fabricated at the lathe machine shop in Samaipur-Badly industrial area, located at a distance of five kilometres from Delhi Technological University, Delhi.

Out of them, first was without slotted holes, second was with slotted holes without welded nuts and third was with slotted holes with welded nuts. Some model steel piles were cut into two halves. Outer ends of steel pile halves along lengthwise were welded with one face of 25 cm x 25 cm angle iron and the other face of angle iron was vertically flush with the outer ends all along its length. Nuts were welded in the holes with threaded spikes put from inside of halve of the pile in such a way that its end face of threaded spike was in flush with outer surface of the pile.

All the data that was taken during the experimental tests was compiled and tabulated as per Chapter IV: Experimental Data, Analysis, Results and Discussions of Model Steel Piles, under the sub-title, "Drawings, Tables and Figures" of sub-head, "Experimental Results of Model Steel Piles".

Chapter IV: Experimental Data, Analysis, Results and Discussions of Model Steel Piles, under the sub-title, "Analysis of results" mentioned various improvement factors, "ξ", for a number of model steel piles having special feature. A number of piles along with their photographs have been detailed under the sub-heading of, "Fabrication of Model Steel Piles" through a glance of Photograph Gallery" and their lengths and sizes have been tabulated under, the sub-head, "Experimental Results of Model Steel Piles" of chapter IV: Experimental Data, Analysis, Results and Discussions of Model Steel Piles.

Some photographs of fabrication as well as testing of model steel piles have been depicted below:

Photograph 7: Steel piles being fabricated at the machine lathe shop.

Photograph 8: Steel piles being stacked at pile site for test

Photograph 9: Test laboratory where piles were being tested.

Photograph 10: Threaded spikes being inserted

Photograph 11: Slotted holes-cum-spiked model steel pile (View 1)

Photograph12: Lifting support mechanism, top tightening through vertical rotating assembly

Photograph 13: Pull-out load arrangement through hydraulic jack, pump, lifting support mechanism

Photograph 14: Cover plate for pile cap.

Photograph 15: Spikes arrangement for a model steel pile on a medium scale (not a part of this thesis) (View 1).

Photograph 16: Zig - zag spikes arrangement (Horizontal) for a model steel pile on a medium scale (not a part of this thesis). (View 2)

Photograph 17: Spikes of various diameters and lengths

.

Photograph 18: Zig - zag spikes arrangement (Vertical) (not a part of this thesis).(view 3)

Photograph 19: Slotted holes circular model steel pile.

Photograph 20: Doubly sloped slotted holes circular finned (faced vertically upwards) steel pile with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals.

Fill Material Characteristics

In this chapter, the characteristics of the fill material were described:

1) Geological and Geotechnical study of silty sand.

2) Research on the shear strength of sand and sand with fine material.

3) Engineering implication of side resistance of Plain model steel pile and special featured model steel pile.

The first two topics are independent but combining the knowledge from these areas will help to understand side resistance being developed in proportion to the extent of providing special feature in a model steel pile, thus, leading to estimate pull-out capacity of special featured model steel pile in silty sand i.e. a mix lot of Yamuna dry sand with varied proportions of fines will be, henceforth, known as Yamuna dry sand or dry sand.

Soil mechanics has been developed in the beginning of the 20th century (Verruijt and Van Baars,2007). The need for the analysis of the behaviour of soils arose in many countries, due to the occurrence of accidents, such as landslides and failures of foundations (Wood, 1990). The first important contributions to soil mechanics are due to Coulomb, who published an important treatise on the failure of soils in 1776, and to Rankine, who published an article on the possible states of stress in soils in 1857. In 1856, Darcy published his famous work on the permeability of soils, for the water supply of the city of Dijon where he proposed to empirically relate effective size with hydraulic conductivity of sands. The effect of material variables in the voids of clean sand such as significant proportion of silts and clays could not be fairly predicted by this relationship. In the 17th century, Newton worked on the principles of the mechanics of continua, including statics and strength of materials. Important pioneering contributions to the development of soil mechanics were made by Karl Terzaghi (1942), who described the influence of the pore water pressures on the behaviour of soils.

The sand is normally found in nature with varied proportion of fines. The soil in the lower reaches and plain area of river basin contains either silt or clay or both in certain proportion depending upon hydro-geological factor. The sand containing varied percentage of silt is called silty sand and is predominantly found in nature. The silty sand was one of the most prominent engineering materials ever since the human settlement started. Some of the preliminary references about the behaviour of silty sand is available in the Sanskrit text of early Aryan civilisation which states that the hydraulic conductivity of this material is such that it has free draining potential for the flow of water. The free flowing behaviour of silty sand indicates possibility of large void space available for the drainage of water through this material which made it a highly valuable media for cultivation and settlement of early civilization. The early Roman empires constructed road for the expansion and control of their kingdom. They removed surface material and replaced it by finished rocks.

Mohr was the first to present a generalised form of the theory in the year 1800for the evaluation of the shear strength of the granular sand. Mohr theory of failure states that the failure of soil due to shear stress depends upon normal stresses on the potential failure plane and the failure is caused by a critical combination of normal and shear stresses. Mohr proposed that shear strength of soil at failure is a unique function of normal stress acting on that plane and is represented by following expression,

$$\tau_f = f(\sigma) \quad (1)$$

A plot drawn between normal stress and shear stress at failure using Eq. (1) is called Mohr's envelope and represents a unique failure envelope for each soil. Coulomb (1776) introduces the idea that shear resistance developed on a soil mass under normal loading is a function of cohesion and frictional resistance between soil particles. Using the concept of Mohr, Coulomb developed a more general relation by considering cohesion between soil particle (c) and angle of internal friction (ϕ), known as Mohr–Coulomb failure criterion**.** This relation is a linear fit expressed as

$$\tau = c + \sigma \tan \Phi \quad (2)$$

For cohesion less soil the Eq. (2) reduces to

$$\tau = \sigma \tan \Phi \quad (3)$$

This is a form of Eq. (1). The failure occurs when the stresses are such that the Mohr circle has a common tangent as the failure envelope as shown in Fig.1. It is clear that the failure occurs if the stresses σ and τlie on or above the failure plane. Point lying below failure envelope represents a stable condition.

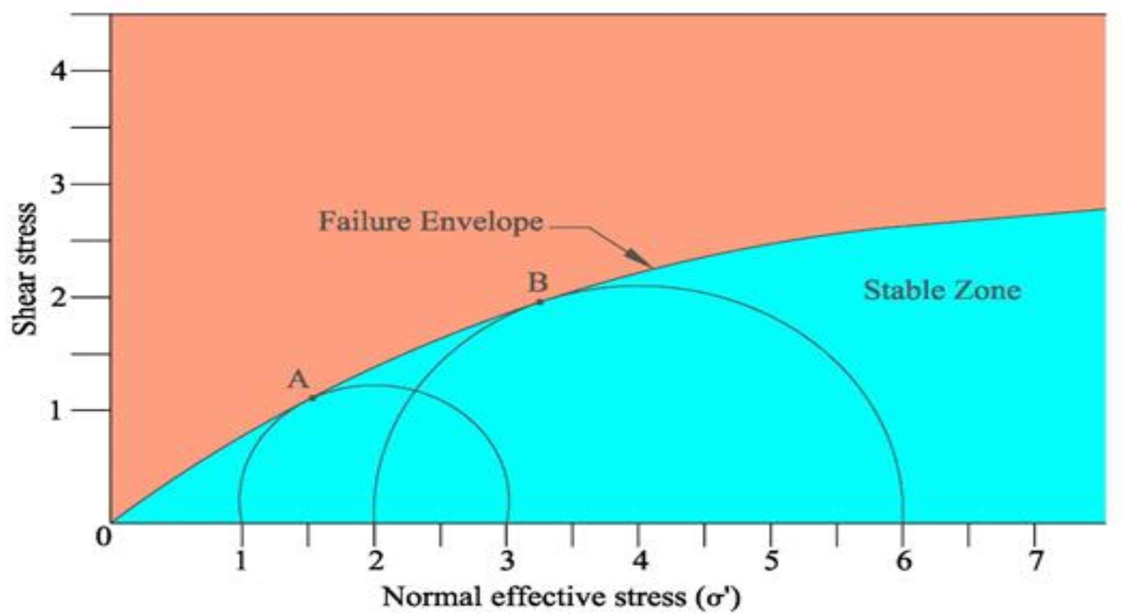


Figure1: Shear stress and normal stress plot for Yamuna sand (Ojha and Trivedi, 2013)

Later the outstanding contribution of Rankine (1862) and Boussinesq (1885) to stress field analysis and latter's correct treatment of tension crack problem led to the evaluation of lower bound solution for the critical height of the vertical cut. Rankine (1862) worked out a unified approach to slope stability and earth pressure for sand and for clays in the long term condition using a simple and practical approach, popularly known as Rankin's theory of earth pressure.

Further the research done by various investigators showed that the parameter c and ϕ depends upon numbers of factors such as water content, drainage conditions, and methods of testing and is not necessarily the fundamental properties of soil. Terzaghi (1948) established that the normal stresses that controls the shear strength of the soil are effective stresses and not normal stresses, and modified the Eq. (2) as

$$\tau = c' + \sigma' \tan \Phi' \; (4)$$

Here c' *and* ϕ' are the cohesion intercept and angle of internal friction in terms of effective stresses. Eq. (4) is known as revised Mohr-Coulomb equation for shear strength of soil.

Characteristics of Clean and Silty Sand

Soils can be classified on the basis of the grain size of the particles that constitute the soil [Trivedi and Sud, 2002, 2007; Shanthakumar et al., 2010]. Coarse granular material is often denoted as gravel and finer material as sand. Soil classification deals with the systematic categorization of soils based on distinguishing characteristics as well as criteria that dictate choices in use. There are many classification system based upon different parameters for classification of sand particles. AASHTO Soil Classification System was developed by the American Association of State Highway and Transportation Officials, and is used as a guide for the classification of soils and soil-aggregate mixtures for highway construction purposes. The classification system was first developed by Hogentogler and Terzaghi (1929) but has been revised several times since then.

In order to have uniformity IS 1498-1970 gives guidelines based on sieve analysis and particle size. Particles size greater than 4.75 mm, but less than 80 mm have been classified as gravel. Larger particles are denoted as stones. Sand is the material consisting of particles smaller than 4.75 mm, but larger than 0.075 mm. Particles smaller than 0.075 mm and larger than 0.002 mm is denoted as silt. Soil consisting of even smaller particles, smaller than 0.002 mm, is denoted as clay as given in Table 1

Table 1: Classification of soil as per IS 1498-1970

Soil type	Minimum particle size (mm)	Maximum particle size (mm)
Clay	-	0.002 mm
Silt	0.002 mm	0.075 mm
Sand	0.075 mm	4.75 mm
Gravel	4.75 mm	80 mm

In the present work Yamuna sand containing varied proportion of fines (0 to 10%) has been considered and its grain size distribution curve has been drawn. The basic difference between silty and clean sands is in the careful choice of methods to quantify density for a logical and correct evaluation of shear strength and liquefaction (not a subject matter of this thesis) of these soils. Secondly, analysis based exclusively on density and stress state are not sufficient for these materials, as the soil fabricis a key determinant of their behaviour [Leroueil and Vaughan (1990)]. Also, not only the content of fines, but also their water retention pecentage, needs to be properly accounted for proper evaluation of their strength property.

Table 2: Water retention of Yamuna Sand with varied proportion of fines

S.No.	Sample Description	Natural moisture	Sun-dry moisture
1.	Yamuna Sand+ 0% Silt	5-7 %	1-2.5 %
2.	Yamuna Sand + 5% Silt	5-8 %	2-2.5%
3.	Yamuna Sand + 10% Silt	7-11%	2-3.4 %

Water retention of Yamuna Sand with varied proportion of fines having sun-dry moisture has been used in the experimental testing are given in the Table 2 on previous page. In the experimental tests on model steel piles, a mix lot of Yamuna dry sand (will, henceforth, be known as Yamuna dry sand or dry sand with varied proportions of fines having varied sun-dry moisture as per Table 2).

Shear Strength

Shear strength of a soil is defined as the limiting value of the shearing stress that a soil can bear before failure. The shear strength of the soil is mainly due to the frictional forces of the inter particle contacts between the soil grains and meshing of particles, cementation and bonding at particle contacts.

The soil behaviour may be dilative or contractive in volume, when subjected to shear strains depending upon the extent of interlocking of the particles. The expansion of volume of soil results in reduction of its density as well as strength and the peak strength is followed by a reduction of shear stress. The stress- strain curve becomes horizontal and the soil continues shearing at constant volume. This is the stage when the inter-particle bonds are broken. This state of soil at which the shear stress and density remains constant while the shear strain increases is called the critical state or steady state. A critical state line separates the dilatant and contractive states for soil. The volume change behaviour and inter-particle friction depend on the density of the particles; inter granular contact forces, and other factors such as the rate of shearing and the direction of the shear stress. The presences of pore water further results in the reduction of inter granular contact force. The net normal inter granular contact force per unit area is after considering pore water pressure is known as effective stress.

The analysis of shear strength of any soil depend on the methods of estimation of appropriate values of c' and ϕ' accurately [Sladen and Handford, 1987]. Values of c' and ϕ' depend on soil history, type of soil, loading condition and drainage. The purpose of shear strength testing is to determine values for the shear strength parameters c' and ϕ'. The drainage conditions during the test influence the measured values considerably [Soni and Jain, (2008)]. However peak friction angle increase with increase in fine content up to 10% then reduces with further increase in fines due to slippage of silt particles adjacent to sand particles asangle of shearing resistance, φ is 40° (max) (Ojha and Trivedi, 2013).

Table 3: Grain size characteristics of few sands with and without fine content

Sand type	(%) Fines	D_{10} (mm)	D_{30} (mm)	D_m (mm)	D_{60} (mm)	C_c	C_u
Yamuna Sand	0	0.13	0.19	0.225	0.25	1.07	1.852
Yamuna Sand	5	0.12	0.19	0.224	0.25	1.14	1.992
Yamuna Sand	10	0.08	0.18	0.222	0.25	1.84	3.307

Factors Affecting Shear Strength of Soils

The shear strength of the soil can be represented by the stress strain plot of a tri axial test output (a matter not discussed in this thesis). The shear strength of soil depends upon many factors [Poulos, 1989]. The main factors that affect the stress-strain relationship of soils are given on the next page:

Composition of Soil

Mineralogy of soil grains, particle size distribution, shape of particles and water content in the soil mass greatly affects the shear strength of soil.

State of Soil

The state of soil is expressed in terms of initial void ratio, effective principal stress and the effective shear stress. The state of a soil can be defined in terms of relative density or relative compaction. The soil can be described by terms such as loose soil, dense soil, over consolidated, normally consolidated, stiff, soft, contractive, dilative, etc. depending upon the index properties of the soil.

Soil Structure

It depends upon the distribution of soil particles within the soil mass; the pattern of the packed particles and the particle size distribution. Structure of soils is mainly described by terms such as: undisturbed, disturbed, remoulded, compacted, layered, honey-combed, single-grained etc.

Pattern of Loading

The shear strength of soil also depends upon type of loading and the condition under which the shearing takes place. Loading of soil sample under different loading condition like drained, undrained, consolidated drained, and unconsolidated undrained gives different shear strength. Magnitude of the load and the rate of loading also play an important role. It is further affected if the loading is static, dynamic, monotonic or cyclic.

Drained shear strength

The drained shear strength is defined as the shear strength of the soil when pore water pressures (a matter not discussed in this thesis), generated during the course of shearing dissipate during shearing. It is also the case of a dry soil when there is no pore water present in the soil. It is estimated using the Mohr-Coulomb equation. Terzaghi (1942) provided a solution for estimation of shear strength of soil using principle of effective stress.

The shear strength is often approximated in terms of effective stresses by Eq. (4) as

$\tau = \sigma' \tan(\phi') + c'$

where $\sigma' = (\sigma - u)$, is defined as the effective stress. σ is the total stress applied normal to the plane of shearing, and u is the pore water pressure acting on the same plane.ϕ'= the effective stress friction angle, or the angle of internal friction after Coulomb friction.

Relative Density and Relative Compaction

The relative density is used to define the state condition of silty sand when silt content is approximately less than 15percent. It is based on the prediction of maximum void ratio; minimum void ratio and natural void ratio. Alternatively it can also be expressed in terms of maximum unit weight, minimum unit weight and natural unit weight of soil. The correct prediction of relative density is not possible since it is difficult to obtain maximum and minimum unit weight values within a definite accurate range. However, it has been discussed in the present thesis w.r.t. free-fall of dry sand from a certain height.

There are some properties of soil that we must know before performing pile load tests. Following are the list of tests which are conducted in the laboratory before pile load test:

Grain Size Analysis of Yamuna Sand

Thus, the results of the various tests conducted on Yamuna sands with varied proportion of fines are given in this chapter. The main Emphasis of this chapter is to understand the nonlinear engineering behavior of Yamuna sand with varied proportion of fines (a matter not discussed in this thesis). In the later part of this section strength characteristics of Yamuna sand with varied proportion of fines are compared with few other sands. Engineering implication like estimation of bearing capacity of Yamuna sand and evaluation of the liquefaction potential by using the values of Q_{af} and R_{af} for varied proportion of fines in the Yamuna sands are presented in this (a matter not discussed in this thesis).

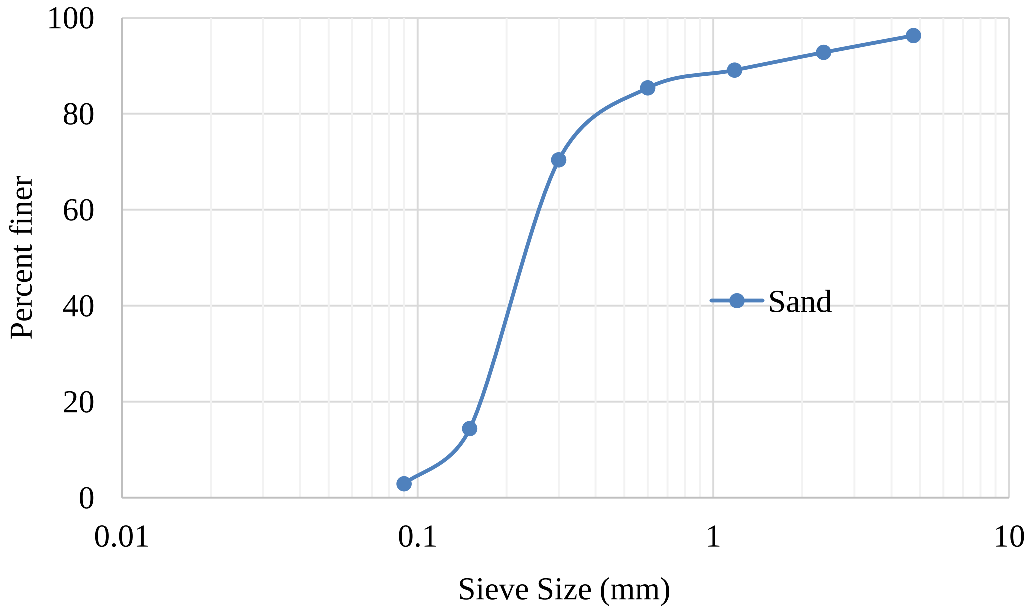


Figure 2: Grain size distribution of Yamuna sand used in the present study

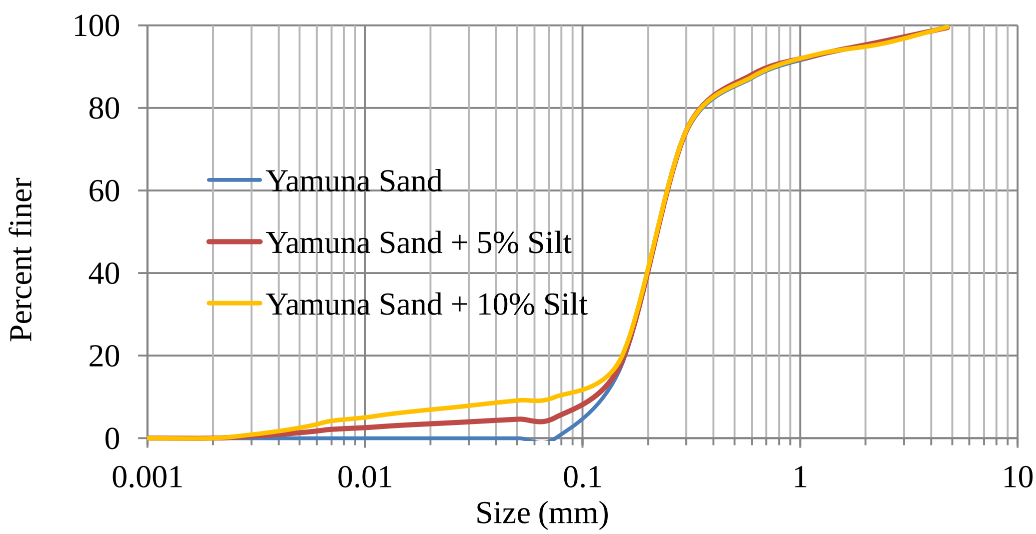


Figure 3: Grain size distribution of crude Yamuna sand along with fines

Classification of Yamuna Sand

The grain size characteristics of Yamuna sand with varied proportion of fines are given in Fig.3. The mean size (D_{50})of Yamuna sand with varied proportion of fines are in the range of 0.208mm to 0.225 mm. Average particle size finer than 60% (D_{60}) varies from 0.24mm to 0.25 mm. Grain size finer than 30% lies between 0.15 to 0.19 mm, while effective size (D_{10}) is in the range of 0.08 to 0.13 mm.

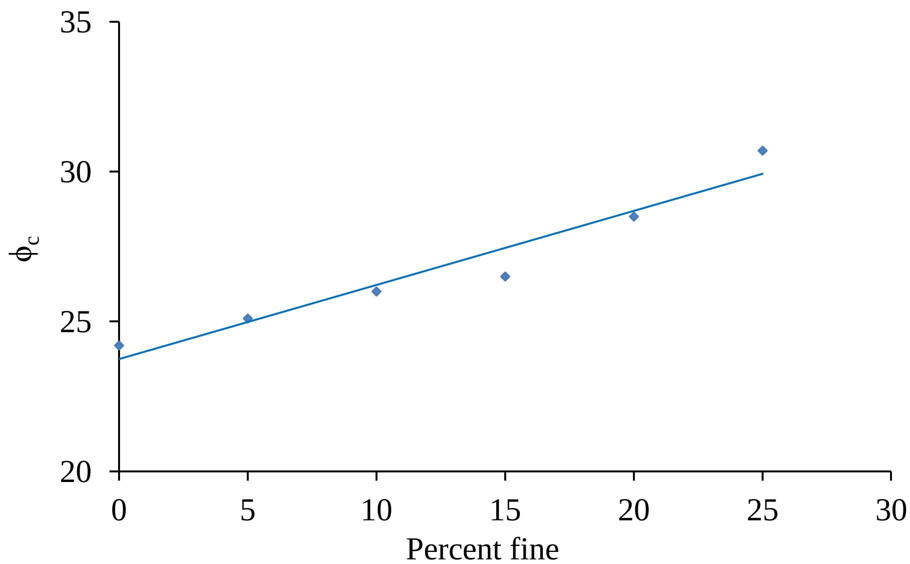


Figure 4: Variation of critical friction angle with percentage fine (Ojha, 2015)

Testing of Model Steel Piles

As has been numerated by number of authors (Agerschou 1962, Flaate 1964, Olsen and Flaate 1967 and Sorensen and Hensen 1957 et al.) that pull-out resistances calculated by theoretical formulae, like, "*Engineering News Record"* formula in particular do happens to provide erroneous results in large variations and hence unreliable. Hence, it has been recommended by number of authors that the best possible practice is to carry out specific pile load tests. (Terzaghi 1943, Poulos 1980 and O'Neil & Reese 1999)

Analysing the literature on side resistance of steel piles, the conclusion drawn by other investigators (Agerschou 1962, Flaate 1964, Olsen and Flaate 1967 and Sorensen and Hensen 1957 et al.) in their view point that the oldest and most frequently used method of estimating the load capacity of driven pile i.e. by driving formulae or dynamic formulae (Poulos and Davis 1980) are unreliable (Agerschou 1962, Flaate 1964, Olsen and Flaate 1967 and Sorensen and Hensen 1957 et al.). Pile-driving formulae attempt to relate the dynamic to the static resistance of a single pile. They have been established on an empirical or a theoretical basis. Many of them are based on Newton's law of impact modified in some cases for energy losses impact and stress propagation. All such formulae relate ultimate load capacity to pile set (i.e. the vertical movement per blow of the driving hammer) and assume that the driving resistance is equal to the load capacity of the pile under static loading (Poulos and Davis 1980). These dynamic formulae were of course developed to overcome the deficiencies of Static formulae (Poulos and Davis 1980).

Smith (1960) states that the editors of *Engineering News Record* have on file 450 such formulae. The derivation of some of these have been discussed by Whitaker (1970), while the whole details of some of the parameters required are available in Chellis (1961).

The primary objective in using a pile-driving formula or static formula are usually either to establish a safe working load for a pile or to determine the driving requirements for a required working load. The working load is usually determined by applying a suitable factor of safety to the ultimate load calculated by the dynamic or static formula. This safety factor however, varies considerably depending on the dynamic or static formula used and the type of pile being driven. Also the static and dynamic formulae do not take into account of the nature of the soil, hence, the appropriate safety factor may vary from one site to another.

The conventional static load test has been believed to be the most reliable test method to obtain the load-settlement relation of a single pile (Matsumoto et al. 2007). However, to obtain a true load-settlement relation, in a static vertical load test, experimental set-up has been constructed in such a way that instead of taking reaction from reaction piles(influenced test piles), it comes from fixed support of steel girder fixed in walls to a true single pile(non-influenced test pile, Matsumoto et al. 2007) via a special arrangement of screw-jack technology converting compressive load into tensile load to determine side-resistance of medium scale model steel piles and large scale model steel piles. The above method comes under the category of pull-out side resistance to determine side resistance. A detailed arrangement has been shown in a neat sketch under the sub-head entitled "Construction of Field Laboratory" of Chapter III: Experimental Programme.

The model steel piles on large scale were tested as detailed in sub-heading of, "Experimental Procedure" of Chapter III: Experimental Programme and their corresponding data was placed into the form of data tables chapter IV: Experimental Data, Analysis, Results and Discussions of Model Steel Piles. From the data tables, corresponding pull-out load vs. extension graphs were made. These plots were drawn with a common scale for comparison.

The comparison for side-resistances of model steel pile without special feature i.e. base model steel pile and with special feature were compared and put into data tables. Results were drawn from data tables and placed into the form of, "ξ factor" a zeta factor i.e. an improvement factor of side resistance of specially featured model steel piles. 2D-Graphs in the form of ξ factor vs. various specially featured model steel piles were drawn and discussed under sub-heading on, "Results and Discussions" in chapter IV: Experimental Data, Analysis, Results and Discussions of Model Steel Piles. The conclusions were drawn and some recommendations were given, in the chapter on, "Conclusions and Recommendations".

Experimental Procedure

First of all, a plain model steel pile was tested. Then, for another test, before a model steel pile was taken for an experimental testing, it had to be very clear that a model steel pile that was to be tested had slotted holes of 10 mm internal dia. with welded nuts of 8 mm internal dia. with internal threading having a pitch equivalent to that of spike threads.

After finishing five experiments with 8 mm dia. spikes with various lengths of 2 cm, 4 cm, 6 cm, 8 cm and 10 cm, all welded nuts of 8 mm int. dia. were removed and re-welded with nuts of 10 mm int. dia. At the last, one model steel pile was tested with welded nuts of internal dia. 10 mm that were in flush with the outer surface of the model steel pile. Then, seven experiments were done with Doubly sloped circular finned (faced vertically upwards) model steel pile with plain finned, slotted holes-cum- finned, welded nuts-cum-finned and spiked- cum- finned model steel piles.

After the model steel piles were driven, then, with the help of long steel spanner, the spikes were rotated

An experimental model steel pile was placed at a right position after proper alignment w.r.t. centre of steel girder where reaction from roof truss was taken straight to the centre of pile via. Hydraulic jack. Then, two dial gauges were placed diametrically opposite to take care of uneven differential settlement. Mean of two dial gauges reading was taken corresponding to every incremental loading. Model steel piles were pile-jacked into its proper position and then the spikes were made out of slotted holes by a very simple technique. The Load is measured for desired extension at number of times till the pile comes out with in a quick succession. An ultimate load is noted for every extension. A dial gauge had least count equal to 1.25 kN. Readings were taken in a diary and transferred to Microsoft Excel sheet. The plots have been made and compared using a Zeta factor i.e. ξ - an improvement factor.

Photograph 21: Pull-out arrangement.

Photograph 22: Load application arrangement.(View1)

Photograph 23: Load application arrangement(View2)

Photograph 24: Load application arrangement(View3)

Photograph 25: Doubly sloped pile being driven

Photograph 25: Two halves were being nut-bolted through

Welded angled-iron.

Experimental Results of Model Steel Piles:

Under the controlled conditions of the soil deposits in the chamber, varied pile sections were placed inside the fill to conduct the pull-out test as per the testing techniques described in the chapter III: Experimental Programme. Steel piles of various sections were considered for evaluating experimental outcome of the pull-out test as described below:

Specifications of Model Steel Piles for Experimental Test:

- Plain model steel pile (MSP). Weight of pile = 38 kg. The Geometrical description and specifications are depicted in Drawing 1. The corresponding results are depicted in Table 4 and Figure 5.
- Slotted holes model steel pile. Weight of pile = 37.5 kg. The Geometrical description and specifications are depicted in Drawing 2. The corresponding results are depicted in Table 5 and Figure 6.
- Welded nut slotted holes model steel pile. Weight of steel pile = 38.25 kg. The Geometrical description and specifications are depicted in Drawing 3. The corresponding results are depicted in Table 6 and Figure7.
- Spike of length 2.0 cm and dia. 10 mm through slotted holes at 90°. Weight of steel pile = 39.0 kg. The Geometrical description and specifications are depicted in Drawing 4. The corresponding results are depicted in Table 7 and Figure 8.
- Spike of length 4.0 cm and dia. 10 mm through slotted holes at 90°. Weight of steel pile = 41.5 kg. The Geometrical description and specifications are depicted in Drawing 5. The corresponding results are depicted in Table 8 and Figure 9.
- Spike of length 6.0 cm and dia. 10 mm through slotted holes at 90°. Weight of steel pile=43.0 kg. The Geometrical description and specifications are

depicted in Drawing 6. The corresponding results are depicted in Table 9 and Figure10.

- Spike of length 8.0 cm and dia. 10 mm through slotted holes at 90°. Weight of steel pile = 44.5 kg. The Geometrical description and specifications are depicted in Drawing 7. The corresponding results are depicted in Table 10 and Figure11.
- Spike of length 10.0 cm and dia. 10 mm through slotted holes at 90°. Weight of steel pile=46.0 kg. The Geometrical description and specifications are depicted in Drawing 8. The corresponding results are depicted in Table 11 and Figure 12.
- Spike of length 2.0 cm and dia. 8 mm through slotted holes at 90°. Weight of steel pile = 38.5 kg. The Geometrical description and specifications are depicted in Drawing 9. The corresponding results are depicted in Table 12 and Figure 13.
- Spike of length 4.0 cm and dia. 8 mm through slotted holes at 90°. Weight of steel pile=39.5 kg. The Geometrical description and specifications are depicted in Drawing 10. The corresponding results are depicted in Table 13 and Figure14.
- Spike of length 6.0 cm and dia. 8.0 mm through slotted holes at 90°. Weight of steel pile = 40.5 kg. The Geometrical description and specifications are depicted in Drawing 11. The corresponding results are depicted in Table 14 and Figure 15.
- Spike of length 8.0 cm and dia. 8 mm through slotted holes at 90°. Weight of steel pile = 41.5 kg. The Geometrical description and specifications are depicted in Drawing 12. The corresponding results are depicted in Table 15 and Figure 16.
- Spike of length 10.0 cm and dia. 8 mm through slotted holes at 90°. Weight of steel pile = 43.0 kg. The Geometrical description and specifications are depicted in Drawing 13. The corresponding results are depicted in Table 16 and Figure 17.

- Slotted holes-cum-Inclined spikes of length 10.0 cm and dia. 10 mm at 30° inclination at a point w.r.t. positive direction of vertical plumb line. Weight of steel pile = 46.0 kg. The Geometrical description and specifications are depicted in Drawing 14. The corresponding results are depicted in Table 17 and Figure 18.
- Slotted holes-cum-Inclined spikes of length 10.0 cm and dia. 10 mm at 60° inclination at a point w.r.t. positive direction of vertical plumb line. Weight of steel pile = 46.0 kg. The Geometrical description and specifications are depicted in Drawing 15. The corresponding results are depicted in Table 18 and Figure 19.
- Slotted holes-cum-Inclined spikes of length 10.0 cm and dia. 10 mm at 90 º inclinations at a point w.r.t. positive direction of vertical plumb line. Weight of steel pile = 46.0 kg. The Geometrical description and specifications are depicted in Drawing 16. The corresponding results are depicted in Table 19 and Figure 20.
- Slotted holes-cum-Inclined spikes of length 10.0 cm and dia. 10 mm at 120° inclination at a point w.r.t. positive direction of vertical plumb line. Weight of steel pile=46.0 kg. The Geometrical description and specifications are depicted in Drawing 17. The corresponding results are depicted in Table 20 and Figure 21.
- Slotted holes-cum-Inclined spikes of length 10.0 cm and dia. 10 mm at 150° inclination at a point w.r.t. positive direction of vertical plumb line. Weight of steel pile = 46.0 kg. The Geometrical description and specifications are depicted in Drawing 18. The corresponding results are depicted in Table 21 and Figure22.
- Spike of length 10.0 cm and dia. 10 cm through slotted hole inclined at exactly 90° (orthogonal direction). Weight of steel pile = 46.0 kg. The Geometrical description and specifications are depicted in Drawing 19. The corresponding results are depicted in Table 22 and Figure 23.
- Spike of length 10.0 cm and dia. 10 cm through slotted hole inclined at exactly 90◦ (orthogonal direction). Weight of steel pile = 46kg. The Geometrical

description and specifications are depicted in Drawing 19. The corresponding results are depicted in Table 22 and Figure 23.

- Doubly sloped circular finned (faced vertically upwards) steel pile with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals. Weight of steel pile = 46.7 kg. Dry sand was not added manually in between the fins while the steel pile was being driven inside the dry sand. The Geometrical description and specifications are depicted in Drawing 20. The corresponding results are depicted in Table 23 and Figure 24.
- Doubly sloped circular finned (faced vertically upwards) steel pile with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals. Weight of steel pile = 46.7 kg. The Geometrical description and specifications are depicted in Drawing 21. The corresponding results are depicted in Table 24 and Figure 25.
- Doubly sloped slotted holes circular finned (faced vertically upwards) steel pile with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals. Weight of steel pile = 46.1 kg The Geometrical description and specifications are depicted in Drawing 22. The corresponding results are depicted in Table 25 and Figure 26.
- Doubly sloped slotted holes welded nuts-cum-circular finned (faced vertically upwards) steel pile with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals; Weight of steel pile = 46.7 kg. The Geometrical description and specifications are depicted in Drawing 23. The corresponding results are depicted in Table 26 and Figure 27.
- Doubly sloped slotted holes-cum-spiked-cum-circular finned (faced vertically upwards) model steel pile-90° - 06/10 with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals; Weight of steel pile = 53.7 kg The Geometrical description and specifications are depicted in Drawing 24. The corresponding results are depicted in Table 27 and Figure 28.

- Doubly sloped slotted holes-cum-spiked-cum-circular finned (faced vertically upwards) model steel pile-90° - 08/10 with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals; Weight of steel pile = 55.2 kg The Geometrical description and specifications are depicted in Drawing 25. The corresponding results are depicted in Table 28 and Figure 29.
- Doubly sloped slotted holes welded nuts-cum-spiked-cum-circular finned (faced vertically upwards) model steel pile-90° - 10/10 with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals; Weight of steel pile = 56.7 kg The Geometrical description and specifications are depicted in Drawing 26. The corresponding results are depicted in Table 29 and Figure 30.

Specifications of doubly sloped circular finned steel pile:

Weight of circular finned model steel pile	46.7 kg
Length of steel pile	1600 cm
Internal dia. of finned base pile	22.2 cm
External dia. of finned base pile	22.8 cm
External dia. from outside-to-outside of fins	32.8 cm
Cone height	15 cm
Slant height	18.25 cm
Side fins-circular	08 number
Fin to fin height	20 cm
Outside fin dia.	33 cm
Fin width-horizontal	5.3 cm

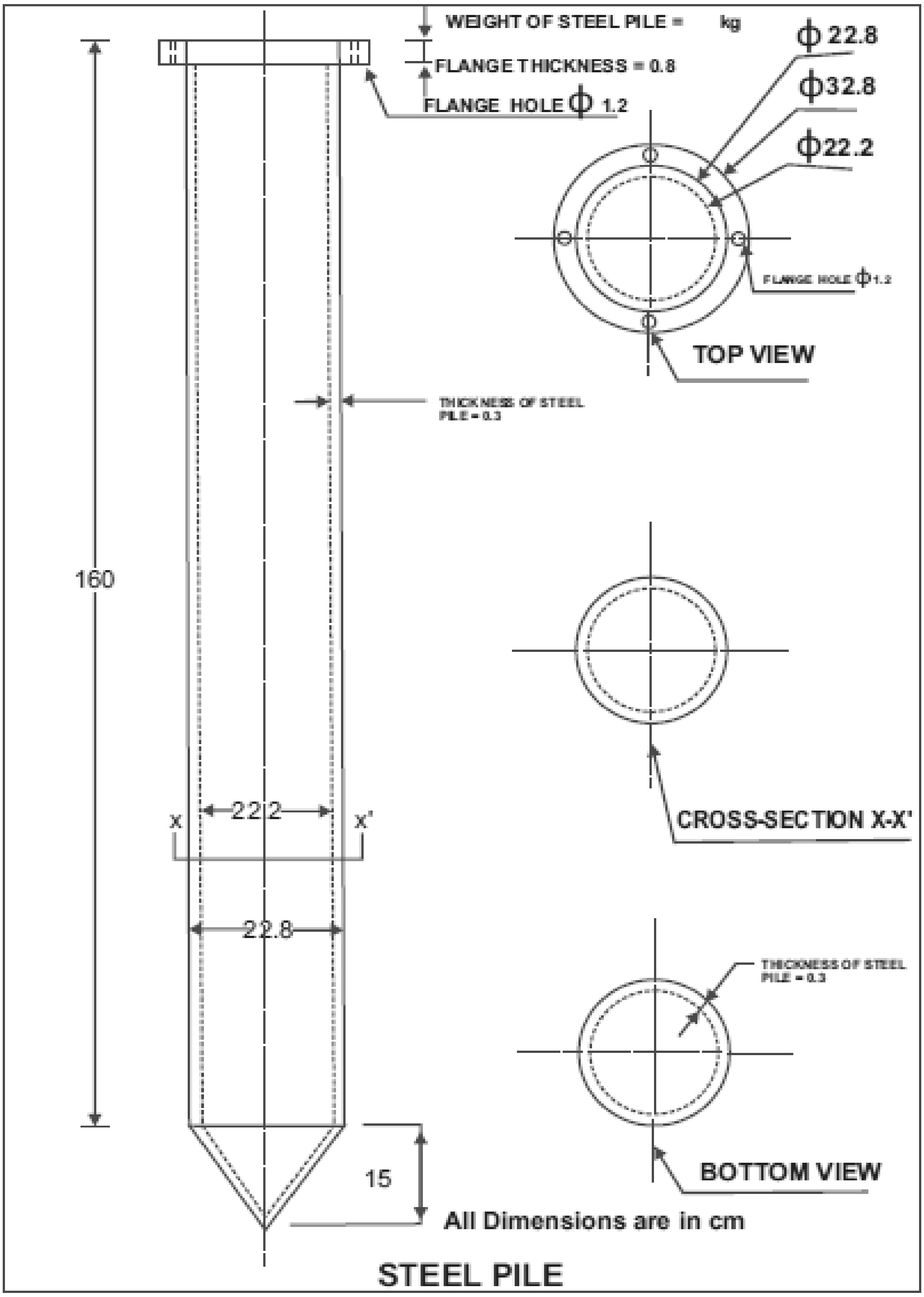
Bottom slant height of fin	8.0 cm
Top slant width of fin	5.3 cm
Distance from fin to hole	2.5 cm

(For doubly slopped slotted holes circular finned pile)

Angle iron to join two cut halves of finned pile	2.5 cm x 2.5 cm
Flange width	5.0 cm
Internal dia. of flange hole	1.2 cm
Weight of flange cover plate	5.6 kg
Weight of 1.2 cm semi- circular iron handle for applying pull-out load	0.8 kg
Nuts and washer	0.1 kg
Number of holes on each halve	04
Total number of circular fins	08
Total number of horizontal rows on each halve	08

The record of pull-out resistance vs. vertical upward displacement is shown in the Table 1 to Table 26 starting from the next page. The corresponding plots are drawn to obtain the peak pull-out resistance respectively and compared with others as shown in Figure 5 to Figure 30. The drawings along with their engineering specifications for varied pile sections are described above as shown in Drawing 1 to Drawing 26.

Drawings, Data Tables and Figures



Drawing 1. Plain model steel pile (MSP) Weight of pile = 38 kg.

Table. 4. Pull-out load vs. Extension for plain model steel pile (MSP)

S. No	Extension (mm)				Cumulative Extension (mm) –ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.04	0.06	0.050	0.05	-0.05	10.00	10.00
2	0.14	0.16	0.150	0.10	-0.15	17.50	27.50
3	0.32	0.37	0.345	0.20	-0.35	7.50	35.00
4	0.47	0.52	0.495	0.15	-0.50	6.25	41.25
5	0.66	0.73	0.695	0.20	-0.70	5.00	46.25
6	0.93	0.98	0.955	0.26	-0.96	6.00	52.25
7	1.18	1.22	1.200	0.24	-1.20	2.50	54.75
8	1.48	1.51	1.495	0.30	-1.50	5.00	59.75
9	1.88	1.91	1.895	0.40	-1.90	3.75	63.50
10	2.33	2.36	2.345	0.45	-2.35	1.25	64.75
11	2.74	2.76	2.750	0.40	-2.75	1.25	66.00
12	Cont. increase	Cont. increase	-	-	Continuous increase	zero	66.00

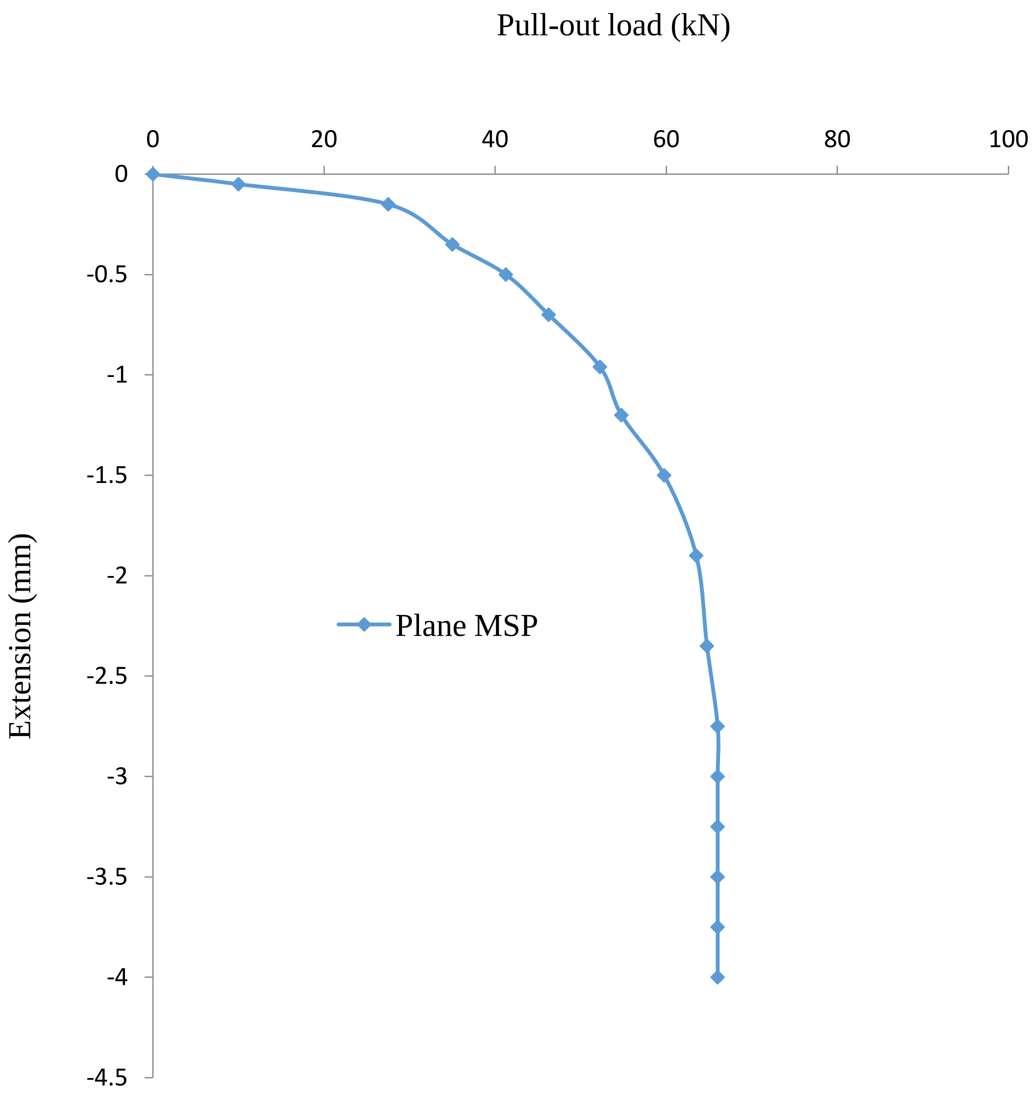
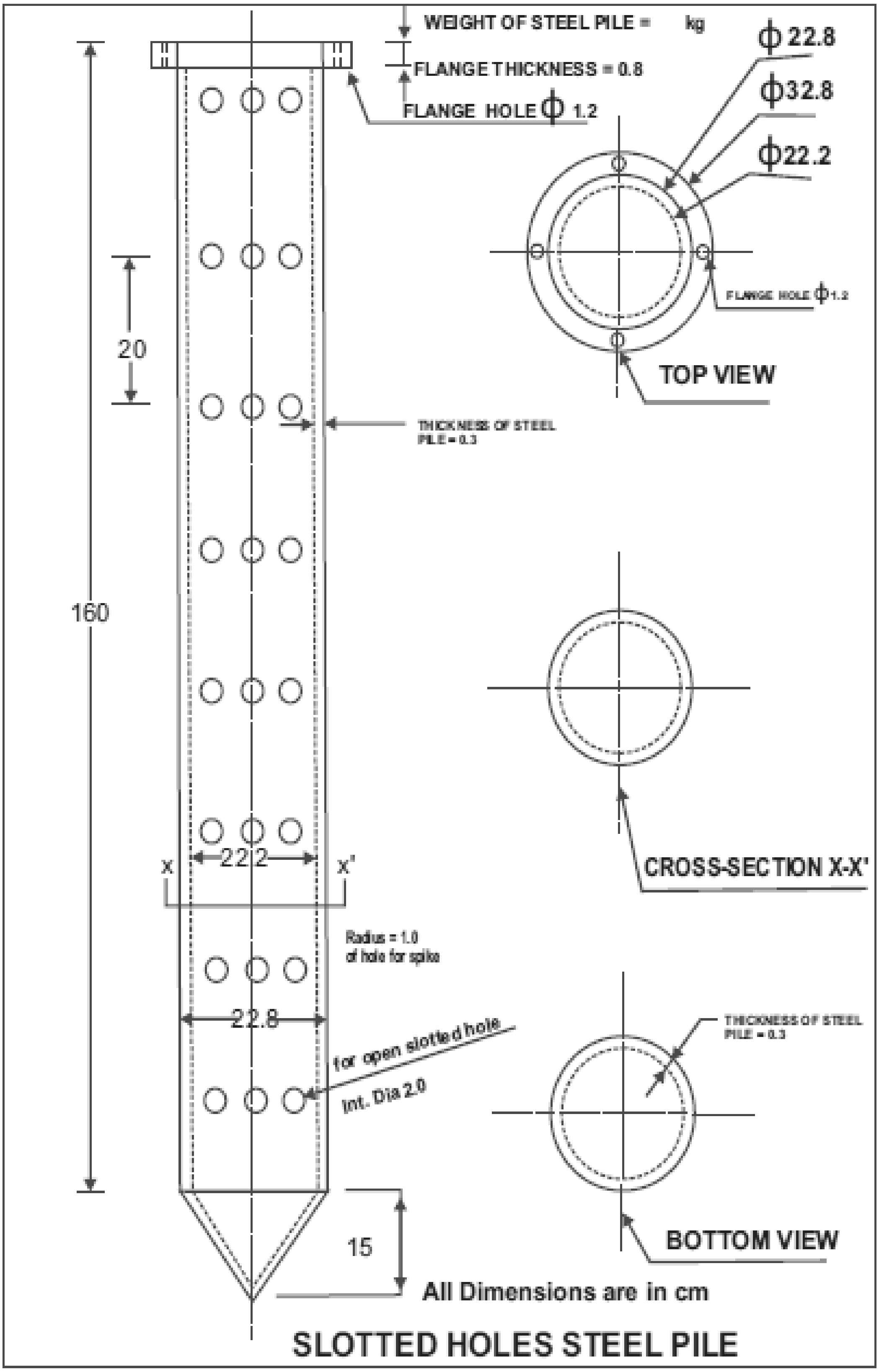


Figure 5: Side resistance of plain model steel pile for MSP



Drawing 2. Slotted holes model steel pile. Weight of pile =37.5 kg.

Table 5. Pull-out load vs. Extension for slotted holes model steel pile

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.050	0.05	-0.05	07.50	07.50
2	0.10	0.10	0.100	0.05	-0.10	02.50	10.00
3	0.14	0.16	0.15	0.05	-0.15	05.00	15.00
4	0.18	0.21	0.195	0.05	-0.20	05.00	20.00
5	0.33	0.36	0.345	0.05	-0.35	10.00	30.00
6	0.38	0.41	0.395	0.05	-0.40	3.75	33.75
7	0.48	0.51	0.495	0.10	-0.50	3.75	37.50
8	0.59	0.61	0.600	0.10	-0.60	16.25	43.75
9	0.69	0.71	0.700	0.10	-0.70	3.75	47.50
10	0.79	0.81	0.800	0.10	-0.80	2.50	50.00
11	0.89	0.91	0.900	0.10	-0.90	3.75	53.75
12	0.99	1.01	1.00	0.10	-1.00	1.25	55.00
13	1.39	1.41	1.40	0.40	-1.40	5.00	60.00
14	1.49	1.51	1.50	0.10	-1.50	2.50	62.50
15	1.79	1.81	1.80	0.30	-1.80	5.00	67.50
16	2.49	2.51	2.50	0.70	-2.50	1.25	68.75
17	2.98	3.01	2.995	0.50	-3.00	1.25	70.00
18	Cont. increase	Cont. increase	-	-	Continuous increase	zero	70.00

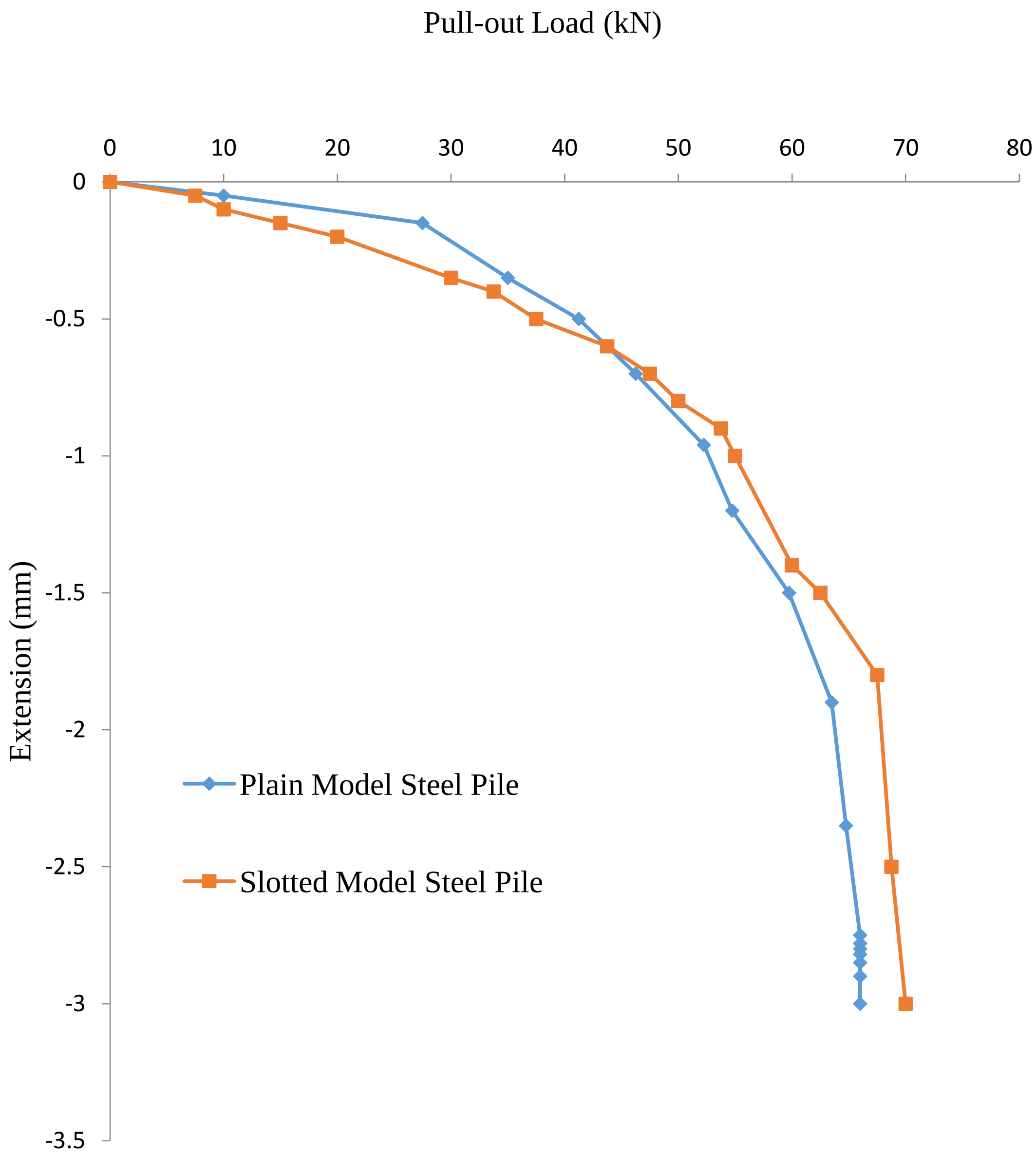
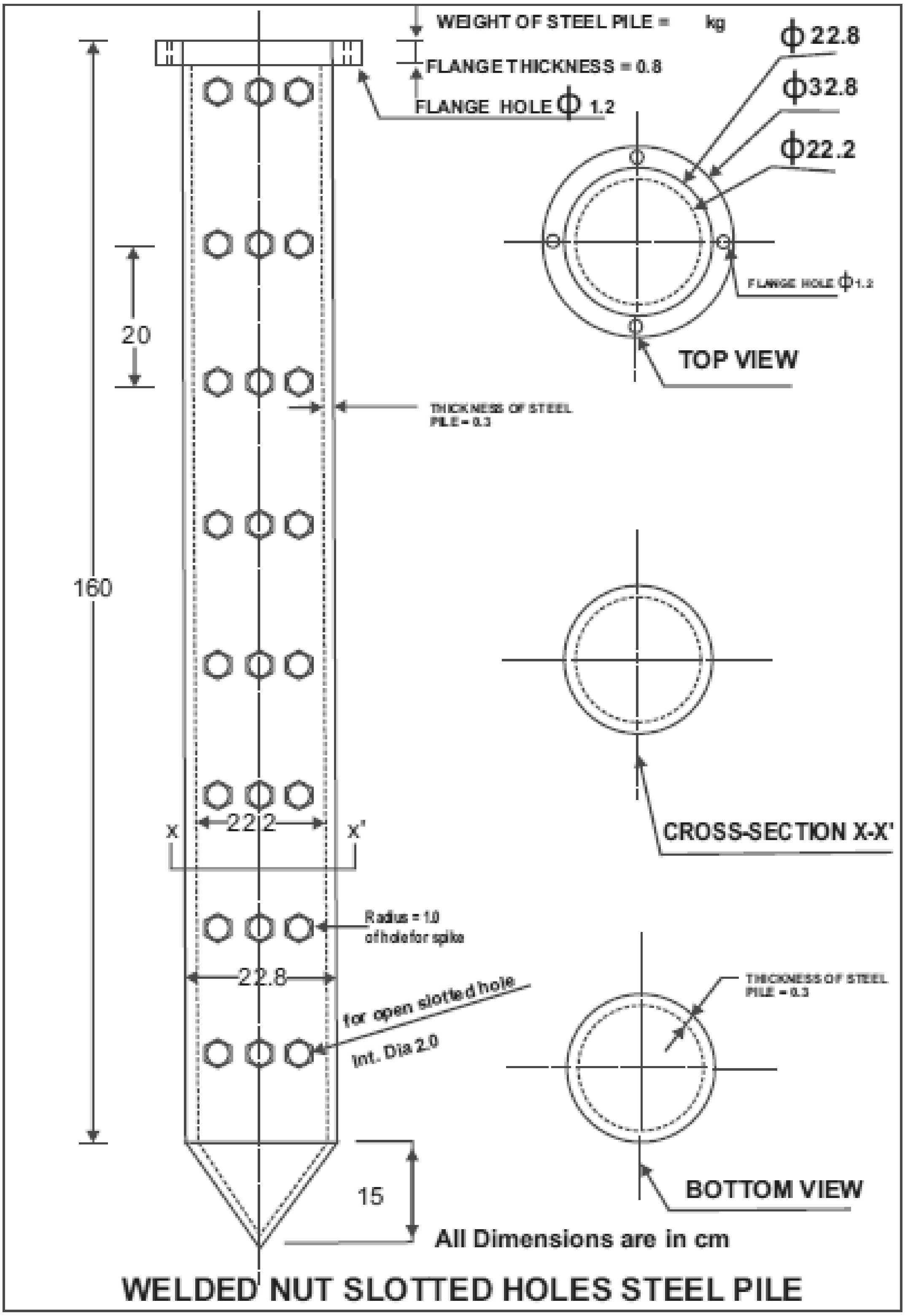


Figure 6: Comparison between side resistance of a plain model steel pile and a slotted model steel pile.



Drawing 3. Welded nut slotted holes model steel pile. Weight of steel pile=38.25 kg

Table 6 Pull-out load vs. Extension for Welded nut slotted holes model steel pile.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	08.75	08.75
2	0.10	0.10	0.100	0.05	-0.10	07.50	16.25
3	0.13	0.16	0.145	0.05	-0.15	12.50	28.75
4	0.24	0.26	0.25	0.10	-0.25	8.75	37.50
5	0.34	0.36	0.35	0.10	-0.35	7.50	45.00
6	0.48	0.51	0.495	0.15	-0.50	5.00	50.00
7	0.73	0.76	0.745	0.25	-0.75	6.25	56.25
8	0.98	1.01	0.995	0.25	-1.00	3.75	60.00
9	1.23	1.26	1.245	0.25	-1.25	3.75	63.75
10	1.48	1.51	1.495	0.25	-1.50	1.25	65.00
11	1.73	1.76	1.745	0.25	-1.75	2.50	67.50
12	1.98	2.01	1.995	0.25	-2.00	2.50	70.00
13	2.23	2.26	2.245	0.25	-2.25	2.50	72.50
14	2.48	2.51	2.495	0.25	-2.50	1.25	73.75
15	2.73	2.76	2.745	0.25	-2.75	1.25	75.00
16	Cont. increase	Cont. increase	-	-	Continuous increase	zero	75.00

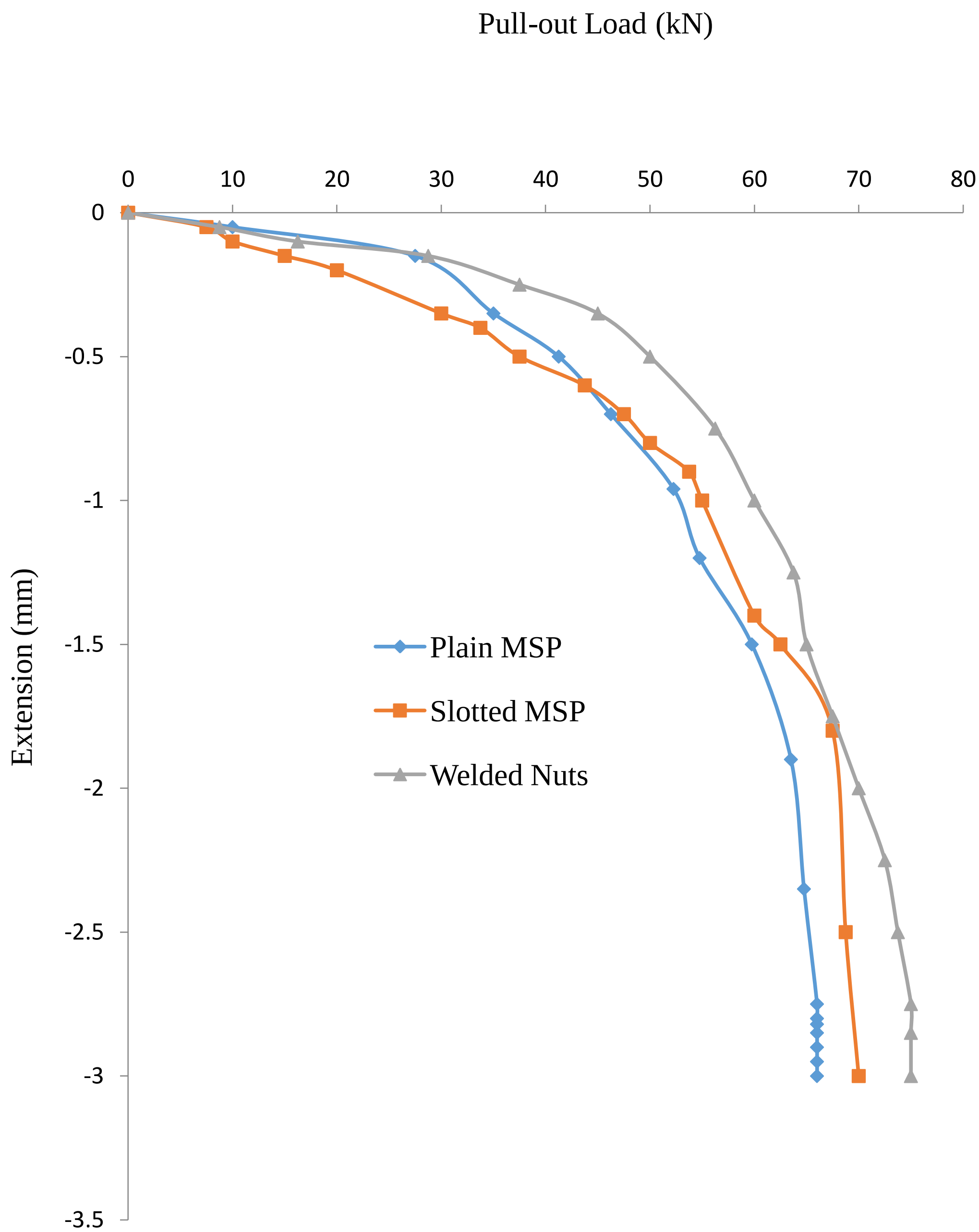
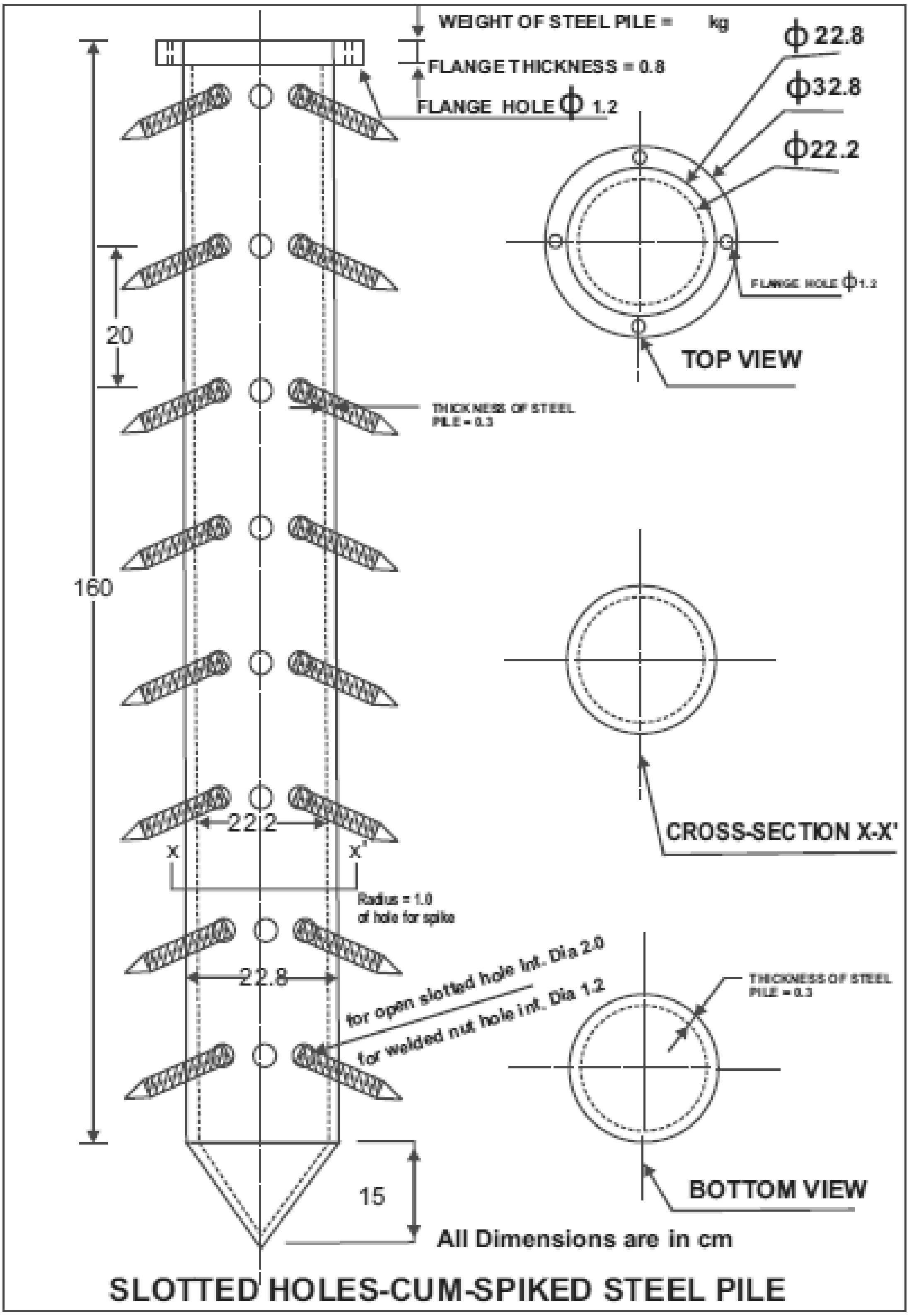


Figure 7: Comparison between side resistance of a plain model steel pile (MSP), a slotted model steel pile (slotted MSP) and a welded nuts slotted holes model steel pile.



Drawing 4. Spike of length 2.0 cm and dia. 10 mm through slotted holes at 90°. Weight of steel pile = 39.0 kg. Spikes coming out through welded nuts having 10 mm int. dia. Nuts are welded behind the hole and inside the pile after cutting it into two halves.

Table 7. Pull-out load vs. Extension for slotted holes-cum-spiked model steel pile. Spiked pile - 02/10 i.e. a model steel pile having length of spikes 02 cm and dia. of spikes 10 mm.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.0	0.05	-0.05	30.00	30.00
2	0.10	0.10	0.10	0.05	-0.10	10.00	40.00
3	0.14	0.16	0.15	0.05	-0.15	2.50	42.50
4	0.19	0.21	0.20	0.05	-0.20	2.50	45.00
5	0.24	0.26	0.25	0.05	-0.25	2.50	47.50
6	0.34	0.36	0.35	0.10	-0.35	2.50	50.00
7	0.44	0.46	0.45	0.10	-0.45	5.00	55.00
8	0.69	0.71	0.70	0.25	-0.70	5.00	60.00
9	0.99	1.01	1.00	0.30	-1.00	5.00	65.00
10	1.34	1.36	1.35	0.35	-1.35	5.00	70.00
11	1.84	1.86	1.85	0.50	-1.85	5.00	75.00
12	2.34	2.36	2.35	0.50	-2.35	5.00	80.0
13	2.74	2.76	2.75	0.40	-2.75	2.50	82.50
14	Cont. increase	Cont. increase	-	-	Continuous increase	zero	82.50

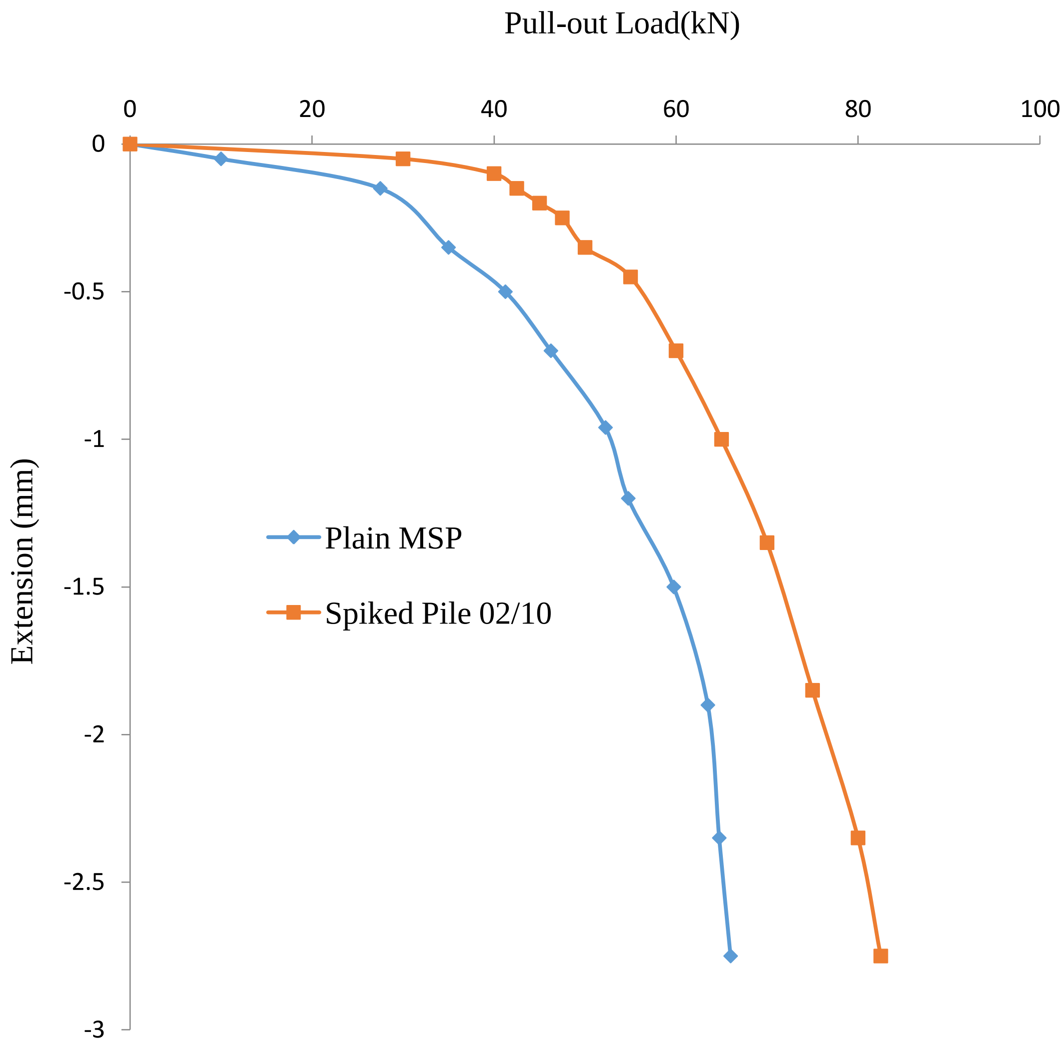
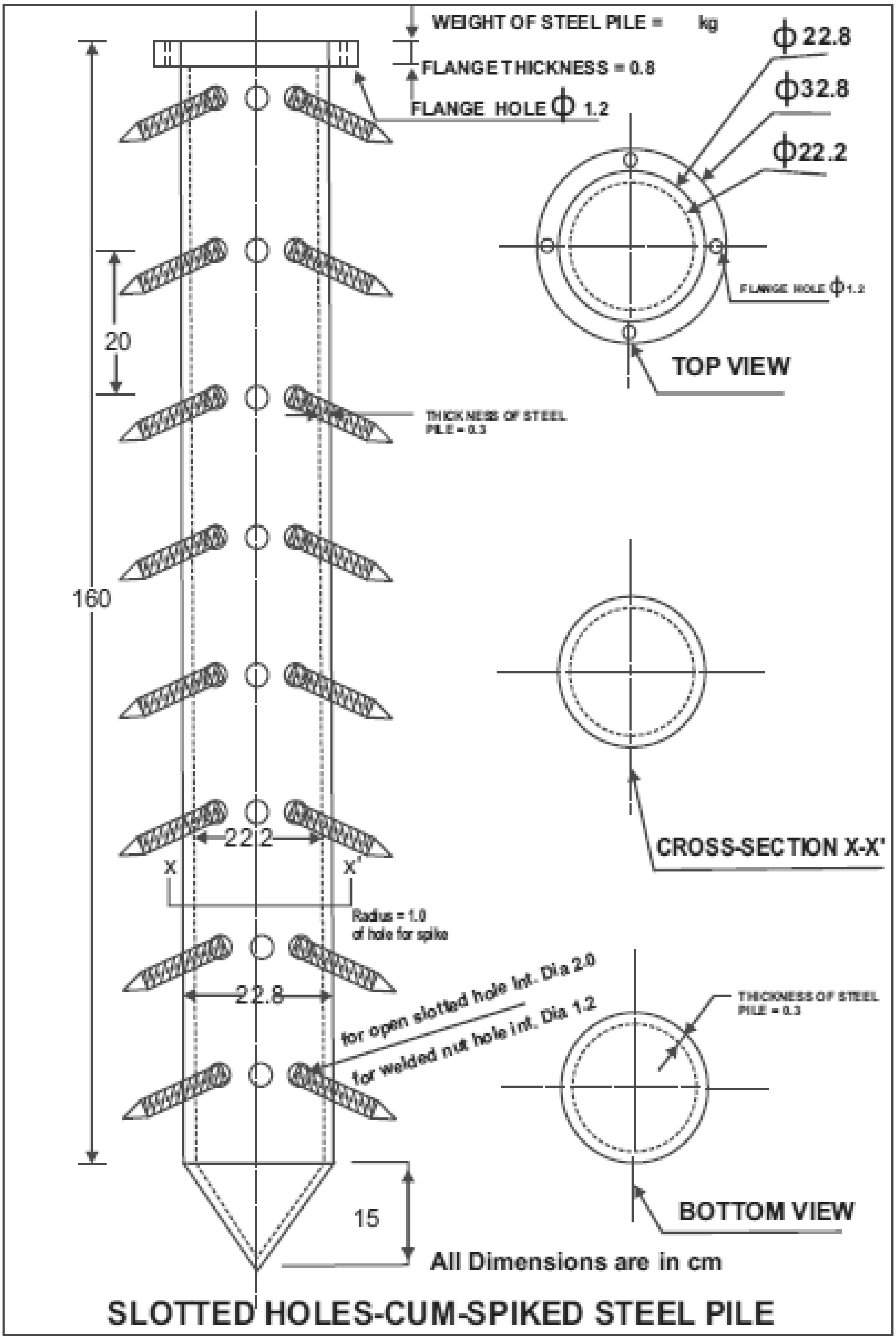


Figure 8: Comparison between side resistance of a plain model steel pile and a spiked model steel pile. Spiked Pile 02/10- a spiked pile having spike length 2.0 cm and dia. of spike 10 mm at 90° respectively



Drawing 5. Spike of length 4.0 cm and dia. 10 mm through slotted holes at 90° degrees. Weight of steel pile = 41.5 kg

Table 8. Pull-out load vs. Extension for slotted holes-cum-spiked model steel pile. Spiked pile-04/10 i.e. a model steel pile having length of spikes 04 cm and dia. of spikes 10 mm.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	46.25	46.25
2	0.10	0.10	0.10	0.05	-0.10	2.50	48.75
3	0.16	0.14	0.05	0.05	-0.15	2.50	51.25
4	0.21	0.19	0.20	0.05	-0.20	3.75	55.00
5	0.36	0.34	0.35	0.15	-0.35	6.25	61.25
6	0.51	0.48	0.495	0.15	-0.50	3.75	65.00
7	0.66	0.64	0.65	0.15	-0.65	5.00	70.00
8	0.91	0.88	0.895	0.25	-0.90	5.00	75.00
9	1.26	1.24	1.25	0.35	-1.25	6.25	81.25
10	1.51	1.49	1.50	0.25	-1.50	3.75	85.00
11	1.76	1.74	1.75	0.25	-1.75	3.75	88.75
12	2.01	1.98	1.995	0.25	-2.00	2.50	91.25
13	2.26	2.24	2.25	0.25	-2.25	2.50	93.75
14	2.51	2.49	2.50	0.25	-2.50	2.50	96.25
15	2.76	2.74	2.75	0.25	-2.75	1.25	97.50
16	Cont. increase	Cont. increase	-	-	Continuous increase	zero	97.50

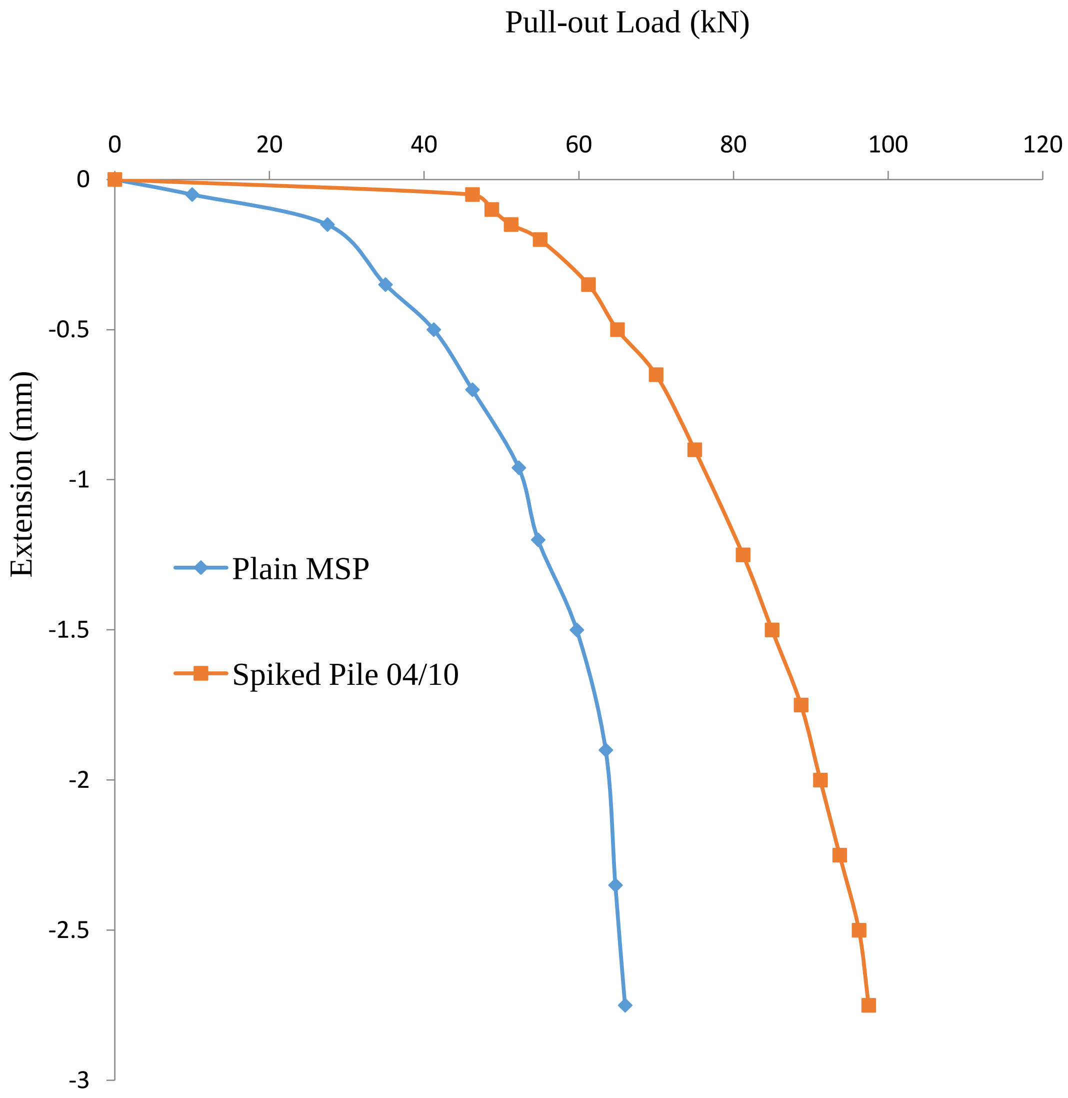
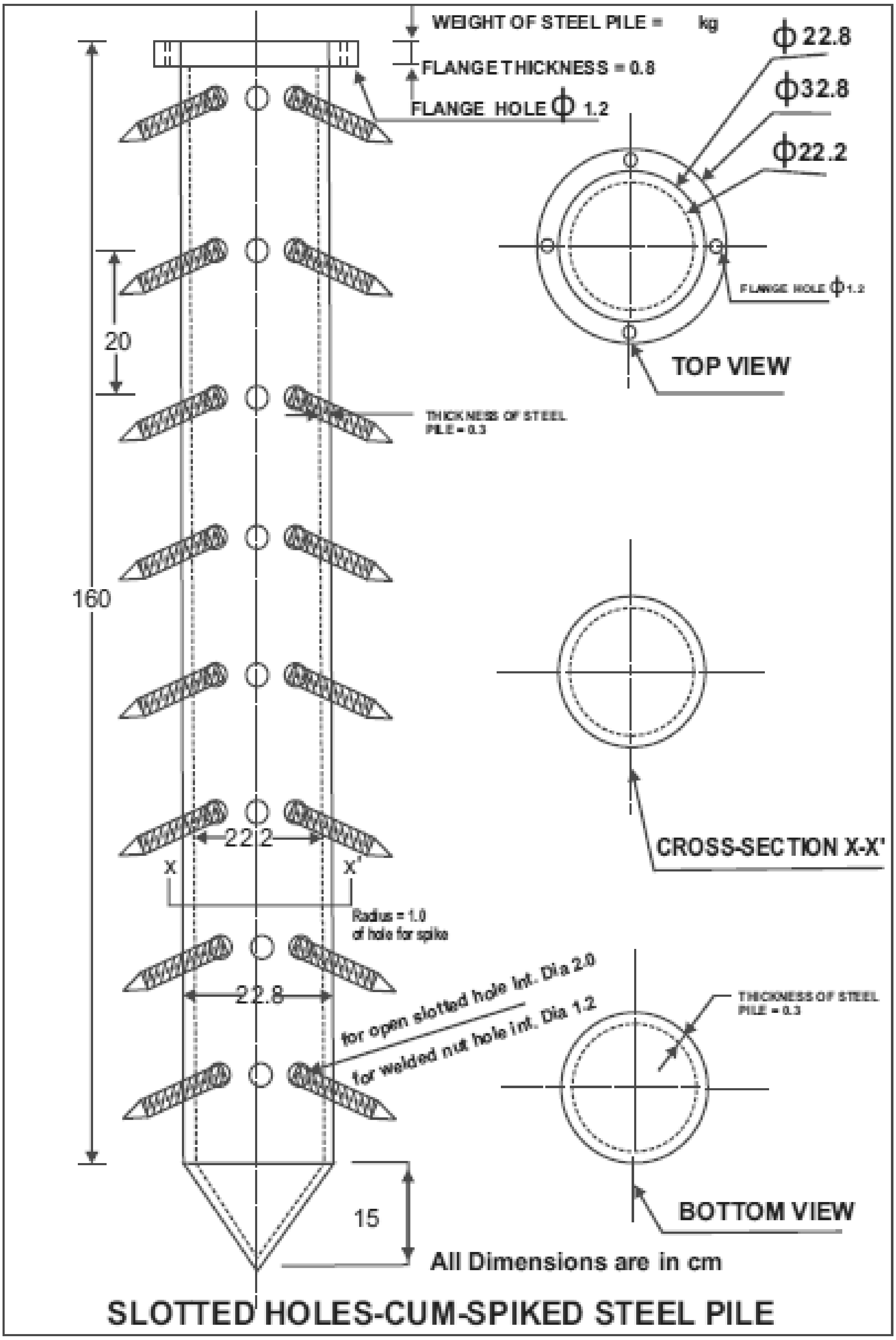


Figure 9: Comparison between side resistance of a plain model steel pile and a spiked model steel pile. Spiked Pile 04/10- a spiked pile having spike length 4.0 cm and dia. of spike 10 mm at 90° respectively



Drawing 6. Spike of length 6.0 cm and dia. 10 mm through slotted holes at 90°.

Weight of steel pile = 43.0 kg

Table 9. Pull-out load vs. Extension for slotted holes-cum-spiked model steel pile. Spiked pile-06/10 i.e. a model steel pile having length of spikes 06 cm and dia. of spikes 10 mm.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.050	0.05	-0.05	65.00	65.00
2	0.10	0.10	0.100	0.05	-0.10	02.50	67.50
3	0.14	0.16	0.150	0.05	-0.15	03.75	71.25
4	0.18	0.21	0.195	0.05	-0.20	02.50	73.75
5	0.24	0.26	0.250	0.05	-0.25	02.50	76.25
6	0.34	0.36	0.350	0.10	-0.35	3.75	80.00
7	0.49	0.51	0.495	0.15	-0.50	5.00	85.00
8	0.74	0.76	0.750	0.25	-0.75	6.25	91.25
9	0.99	1.01	1.000	0.25	-1.00	5.00	96.25
10	1.23	1.26	1.245	0.25	-1.25	2.50	98.75
11	1.49	1.51	1.500	0.25	-1.50	2.50	101.25
12	1.74	1.76	1.750	0.25	-1.75	3.75	105.00
13	1.99	2.01	2.000	0.25	-2.00	1.25	106.25
14	2.24	2.26	2.25	0.25	-2.25	2.50	108.75
15	2.49	2.51	2.50	0.25	-2.50	1.25	110.00
16	2.74	2.76	2.75	0.25	-2.75	1.25	111.25
17	Cont. increase	Cont. increase	-	-	Continuous increase	zero	111.25

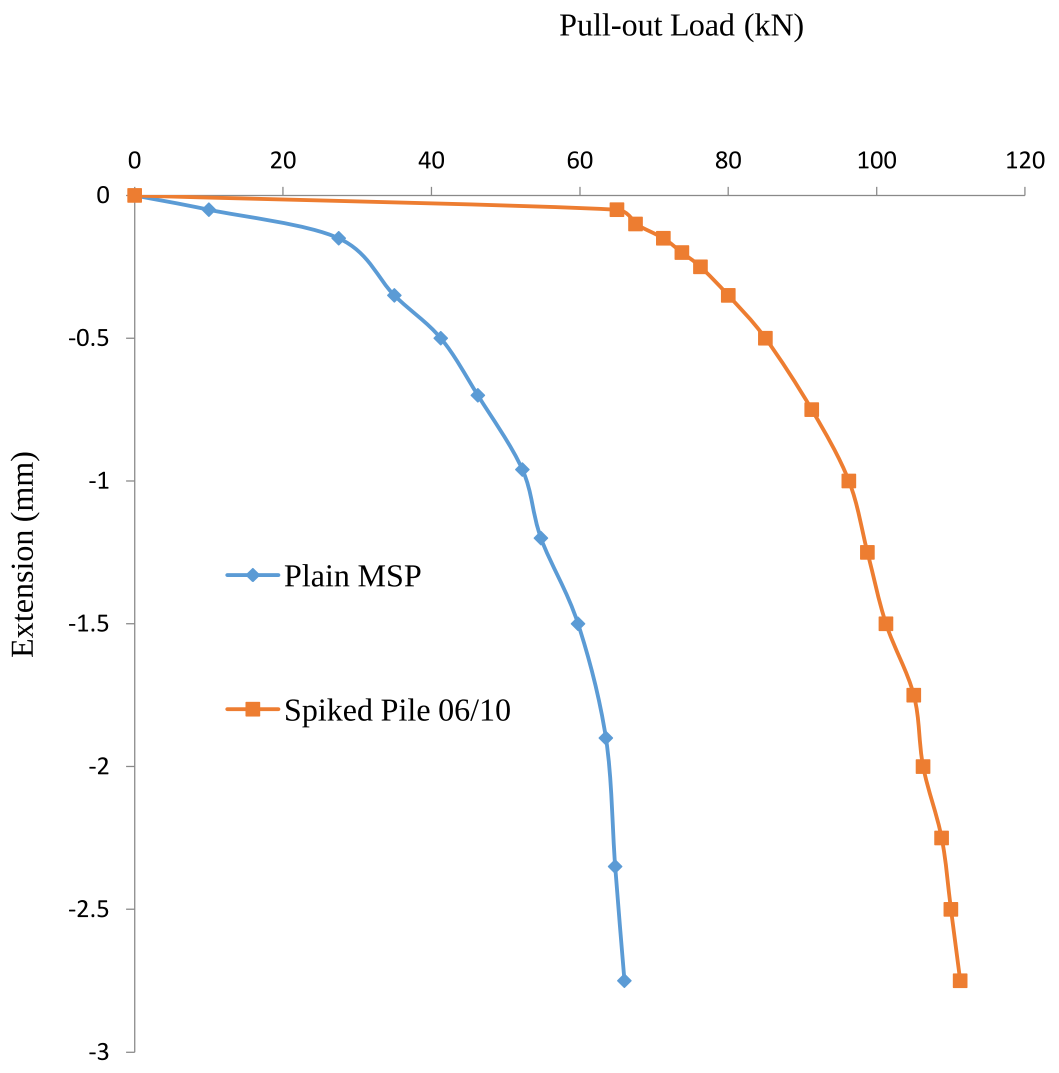
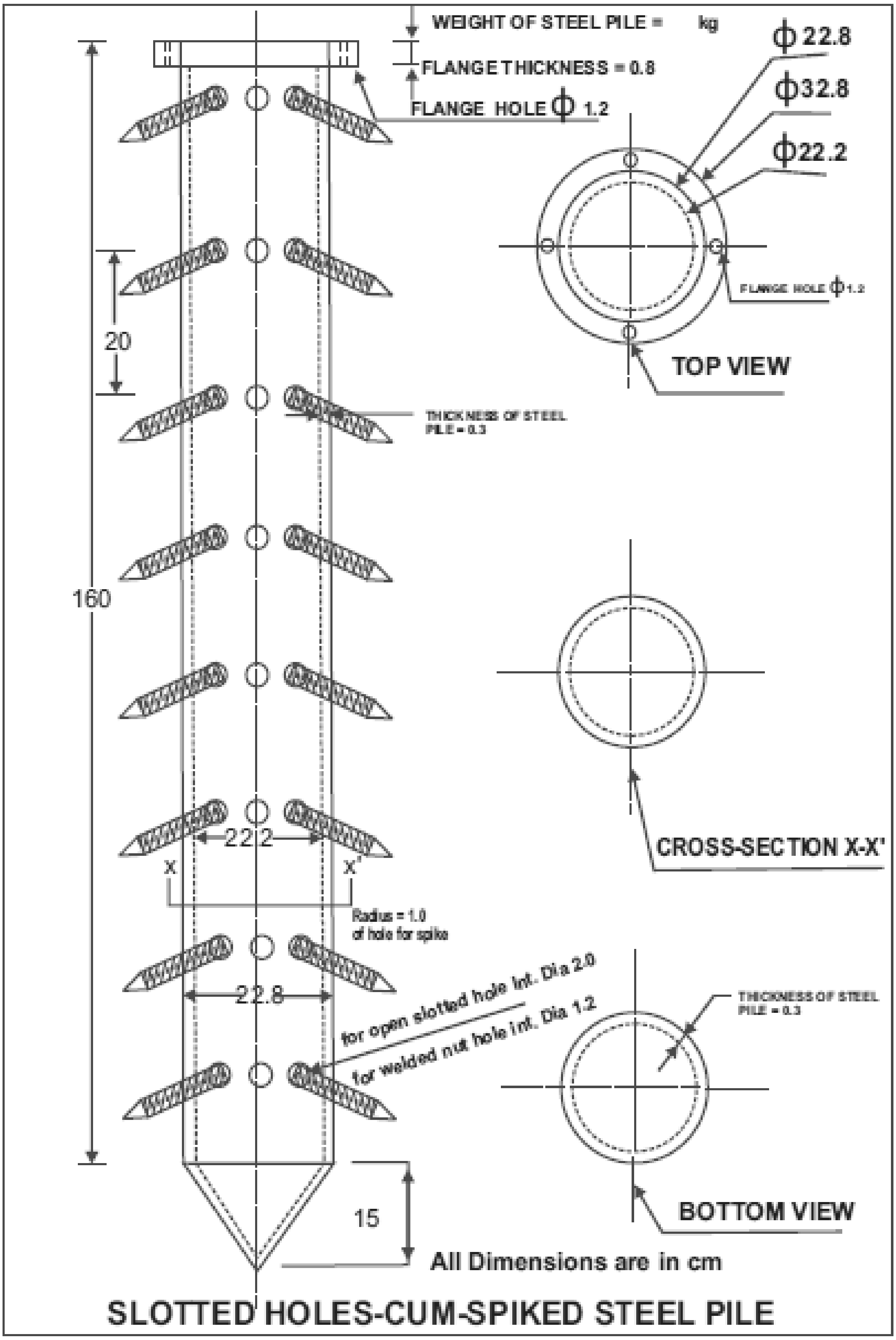


Figure 10: Comparison between side resistance of a plain model steel pile and a spiked model steel pile. Spiked Pile 06/10 - a spiked pile having spike length 6.0 cm and dia. of spike 10 mm at 90° respectively.



Drawing 7. Spike of length 8.0 cm and dia. 10 mm through slotted holes at 90°.Weight of steel pile = 44.5 kg

Table 10. Pull-out load vs. Extension for slotted holes-cum-spiked model steel pile. Spiked pile-08/10 i.e. a model steel pile having length of spikes 08 cm and dia. of spikes 10 mm.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	72.50	72.50
2	0.10	0.10	0.10	0.05	-0.10	10.00	82.50
3	0.16	0.14	0.15	0.05	-0.15	1.25	83.75
4	0.21	0.19	0.20	0.05	-0.20	2.50	86.25
5	0.26	0.24	0.25	0.05	-0.25	1.25	87.50
6	0.36	0.34	0.35	0.10	-0.35	3.75	91.25
7	0.51	0.49	0.50	0.15	-0.50	3.75	95.00
8	0.76	0.74	0.75	0.25	-0.75	6.25	101.25
9	1.01	0.99	1.00	0.25	-1.00	3.75	105.00
10	1.26	1.24	1.25	0.25	-1.25	3.75	108.75
11	1.51	1.49	1.50	0.25	-1.50	2.50	111.25
12	1.76	1.74	1.75	0.25	-1.75	3.75	115.00
13	2.01	1.99	2.00	0.25	-2.00	2.50	117.50
14	2.26	2.24	2.25	0.25	-2.25	1.25	118.75
15	2.51	2.49	2.50	0.25	-2.50	1.25	120.00
16	2.76	2.74	2.75	0.25	-2.75	1.25	121.25
17	Cont. increase	Cont. increase	-	-	Continuous increase	zero	121.25

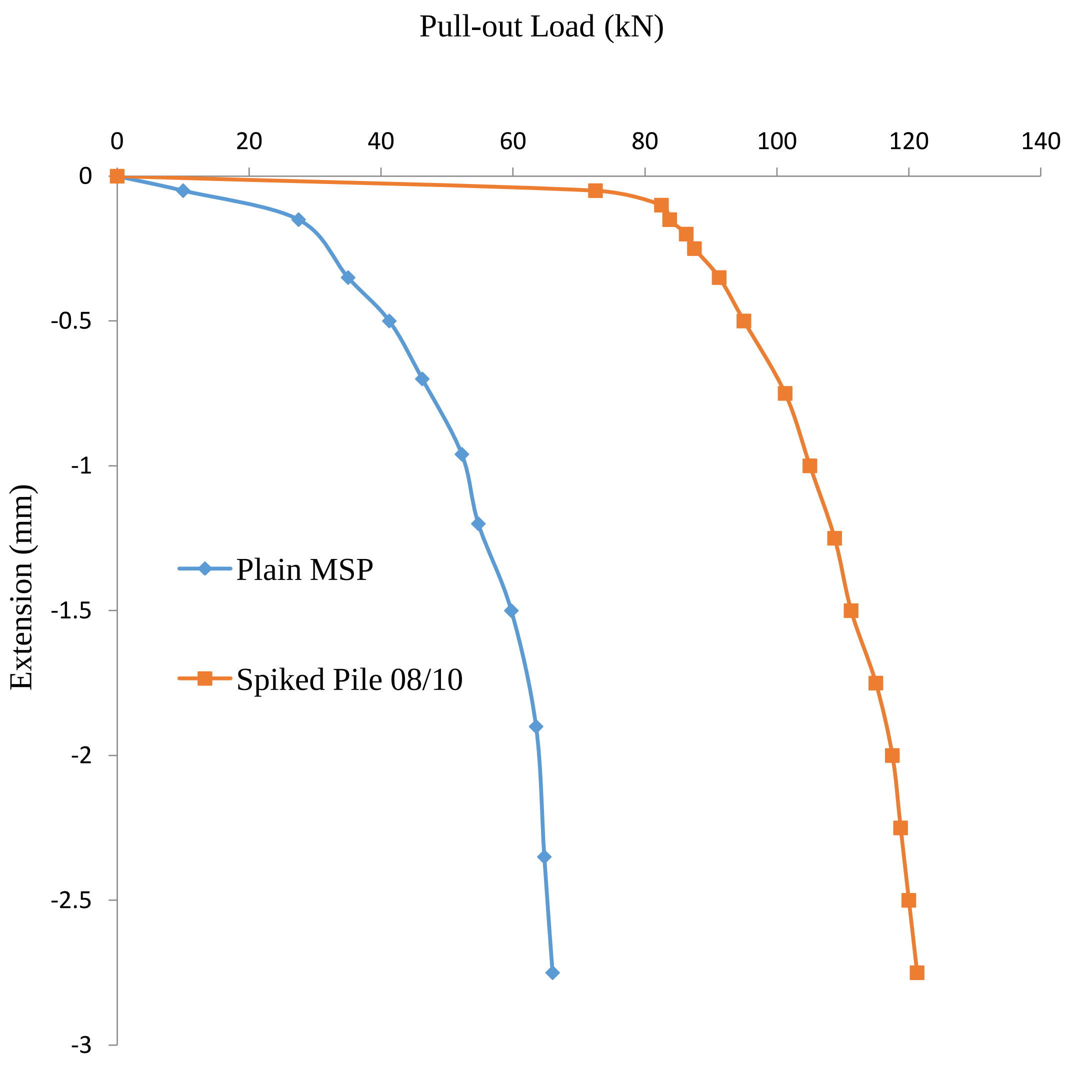
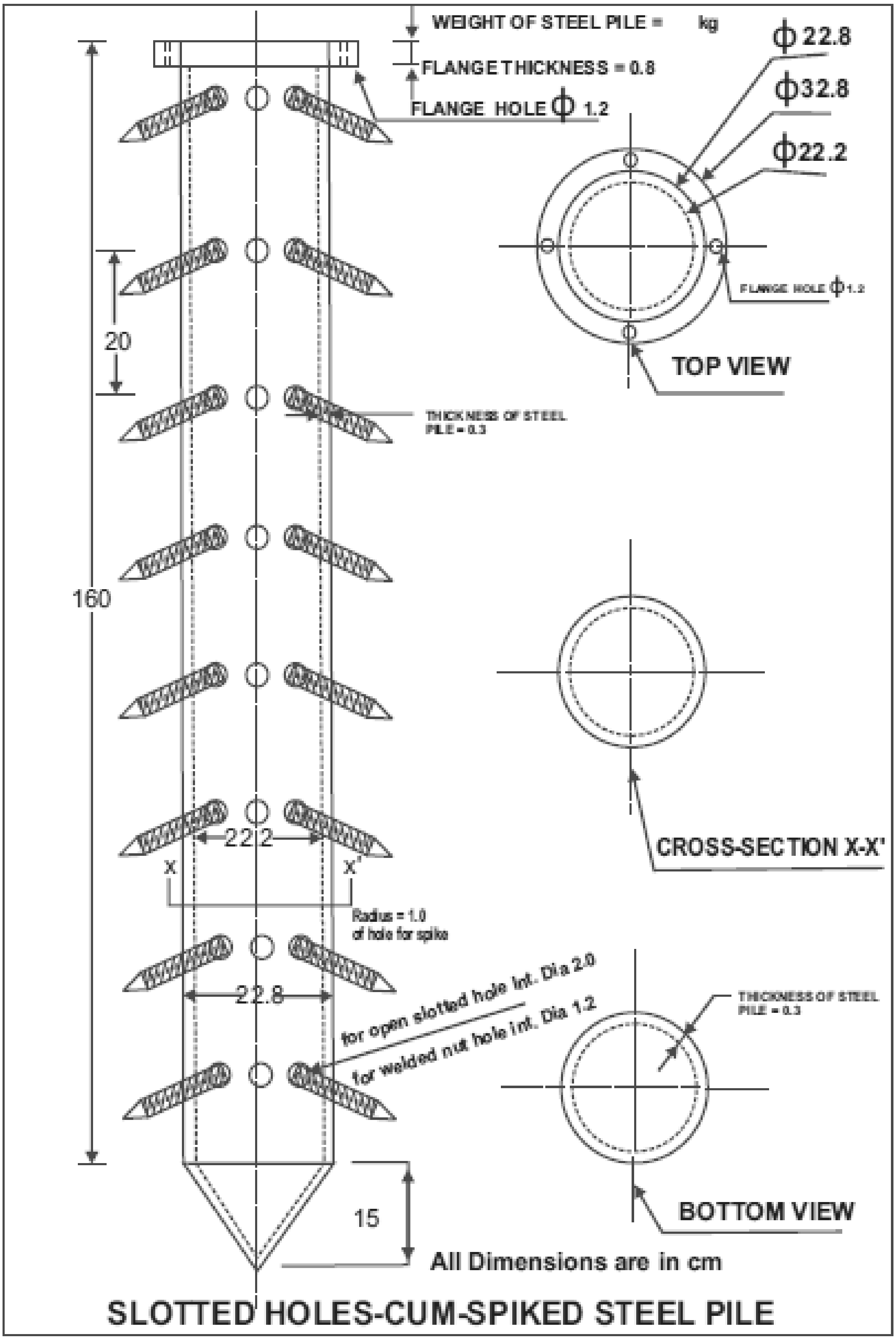


Figure 11: Comparison between side resistance of a plain model steel pile and a spiked model steel pile. Spiked Pile 08/10- a spiked pile having spike length 8.0 cm and dia. of spike 10 mm at 90°respectively



Drawing 8. Spike of length 10.0 cm and dia. 10 mm through slotted holes at 90°. Weight of steel pile = 46.0 kg

Table 11. Pull-out load vs. Extension for slotted holes-cum-spiked model steel pile. Spiked pile-10/10 i.e. a model steel pile having length of spikes 10 cm and dia. of spikes 10 mm.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	83.75	83.75
2	0.10	0.10	0.10	0.05	-0.10	08.75	92.50
3	0.14	0.16	0.15	0.05	-0.15	02.50	95.00
4	0.19	0.21	0.20	0.05	-0.20	02.50	97.50
5	0.24	0.26	0.25	0.05	-0.25	01.25	98.75
6	0.34	0.36	0.35	0.10	-0.35	3.75	102.50
7	0.49	0.51	0.50	0.15	-0.50	2.50	105.00
8	0.74	0.76	0.75	0.25	-0.75	5.00	110.00
9	0.99	1.01	1.00	0.25	-1.00	3.75	113.75
10	1.24	1.26	1.25	0.25	-1.25	3.75	117.50
11	1.49	1.51	1.50	0.25	-1.50	1.25	118.75
12	1.74	1.76	1.75	0.25	-1.75	3.75	122.50
13	1.99	2.01	2.00	0.25	-2.00	2.50	125.00
14	2.24	2.26	2.25	0.25	-2.25	1.25	126.25
15	2.49	2.51	2.50	0.25	-2.50	1.25	127.50
16	2.74	2.76	2.75	0.25	-2.75	1.25	128.75
17	Cont. increase	Cont. increase	-	-	Continuous increase	zero	128.75

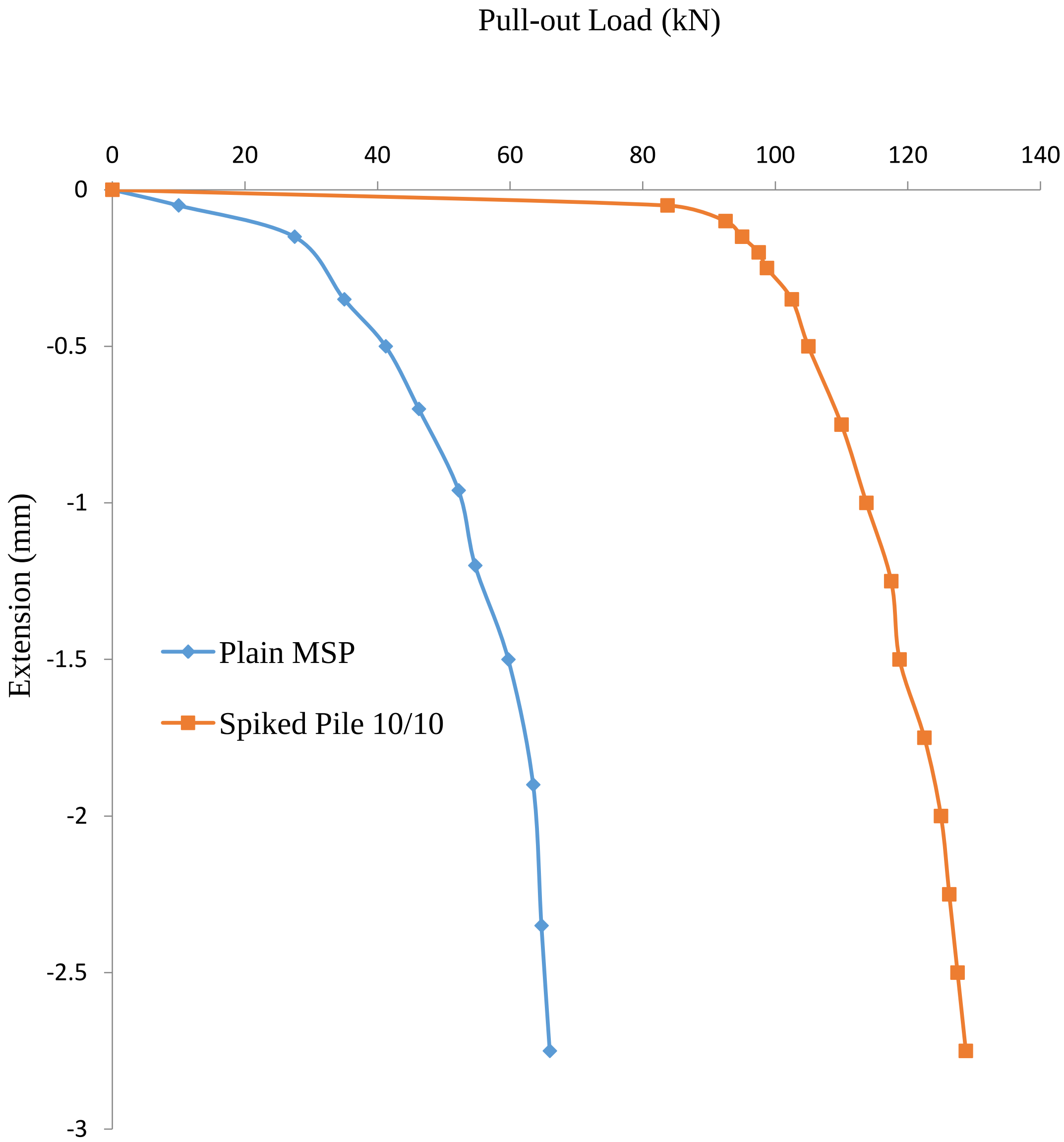
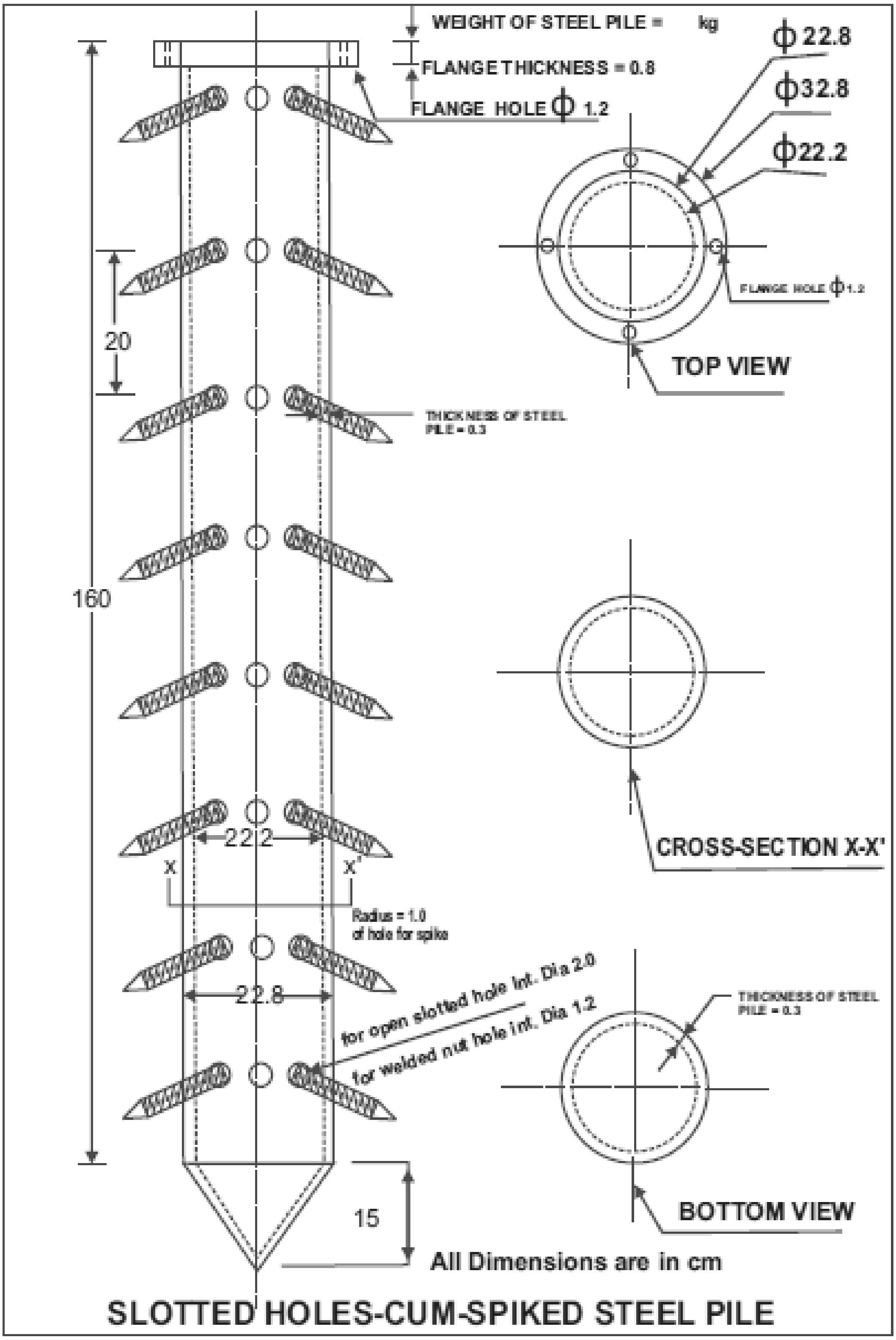


Figure 12: Comparison between side resistance of a plain model steel pile and a spiked model steel pile. Spiked Pile 10/10 - a spiked pile having spike length 10.0 cm and dia. of spike 10 mm at 90°respectively.



Drawing 9. Spike of length 2.0 cm and dia. 8 mm through slotted holes at 90°. Weight of steel pile = 38.5 kg. Spikes coming out through welded nuts having 8 mm int. dia.. Nuts are welded behind the hole and inside the pile after cutting it into two halves.

Table 12. Pull-out load vs. Extension for slotted holes-cum-spiked model steel pile. Spiked pile-02/08 i.e. a model steel pile having length of spikes 02 cm and dia. of spikes 08 mm.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.0	0.05	-0.05	27.50	27.50
2	0.10	0.10	0.10	0.05	-0.10	10.00	37.50
3	0.16	0.14	0.15	0.05	-0.15	2.50	40.00
4	0.21	0.19	0.20	0.05	-0.20	2.50	42.50
5	0.26	0.24	0.25	0.05	-0.25	2.50	45.00
6	0.36	0.34	0.35	0.10	-0.35	2.50	47.50
7	0.46	0.44	0.45	0.10	-0.45	3.75	51.25
8	0.71	0.69	0.70	0.25	-0.70	5.00	56.25
9	1.01	0.99	1.00	0.30	-1.00	5.00	61.25
10	1.36	1.34	1.35	0.35	-1.35	5.00	66.25
11	1.86	1.84	1.85	0.50	-1.85	5.00	71.25
12	2.36	2.34	2.35	0.50	-2.35	3.75	75.00
13	2.76	2.74	2.75	0.40	-2.75	2.50	77.50
14	Cont. increase	Cont. increase	-	-	Continuous increase	zero	77.50

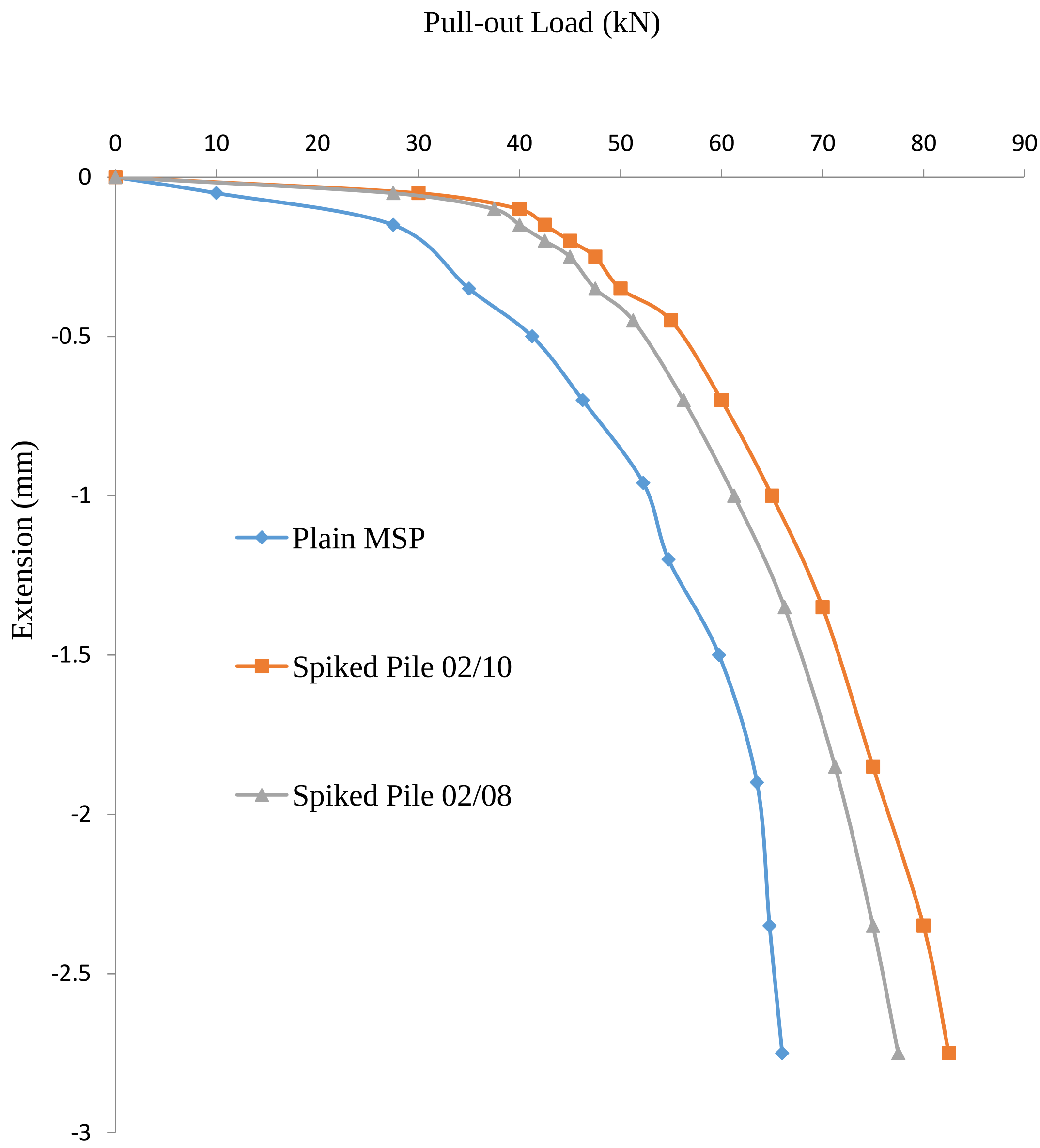
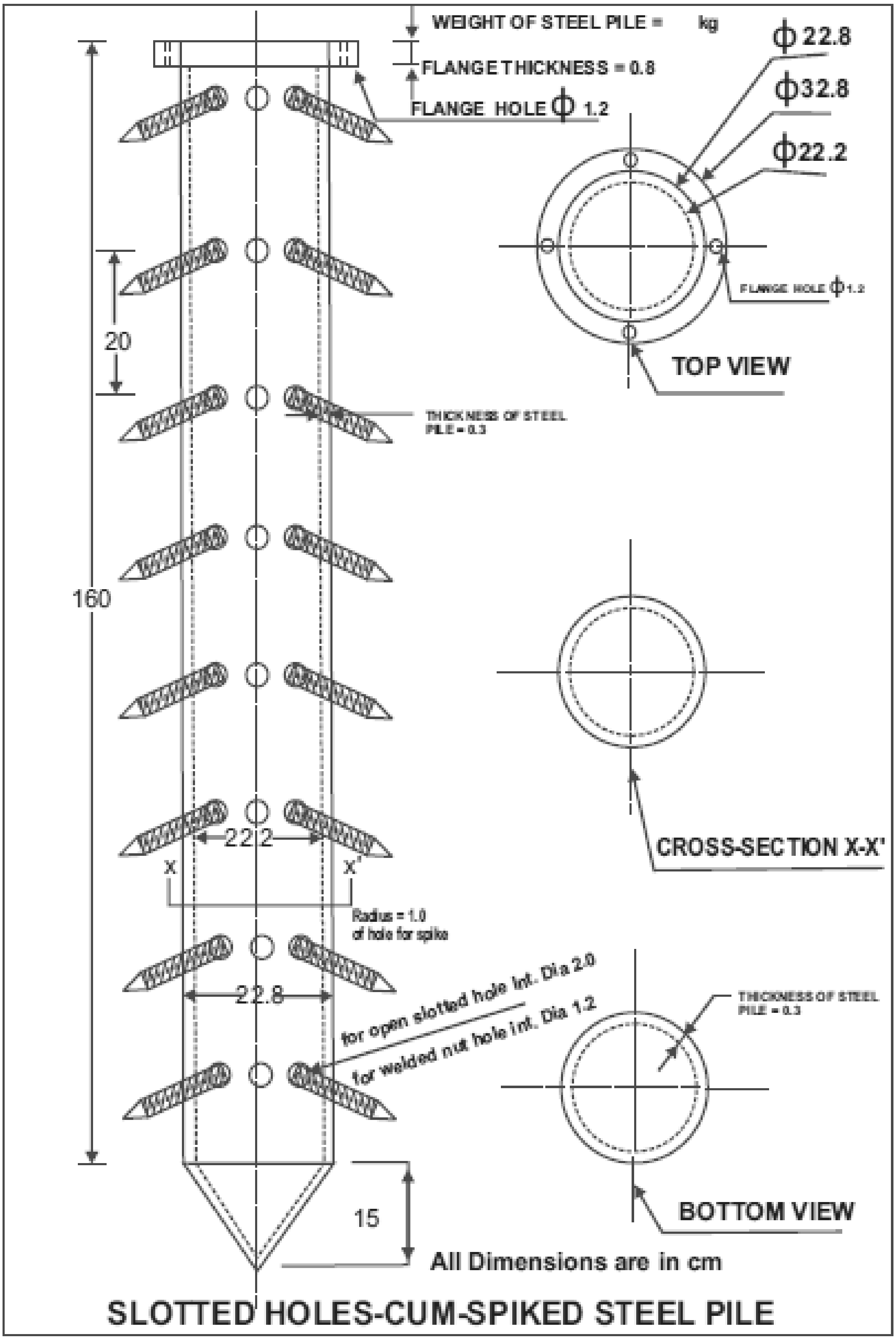


Figure 13: Comparison between side resistance of a plain model steel pile, a spiked model steel pile 02/08 and another spiked pile 02/10. Spiked Pile 02/08- a spiked pile having spike length 02 cm and dia. of spike 08 mm at 90°**.** Spiked Pile 02/10- a spiked pile having spike length 02 cm and dia. of spike 10 mm at 90°**.**



Drawing 10. Spike of length 4.0 cm and dia. 8 mm through slotted holes at 90°. Weight of steel pile = 39.5 kg

Table 13. Pull-out load vs. Extension for slotted holes-cum-spiked model steel pile. Spiked pile-04/08 i.e. a model steel pile having length of spikes 04 cm and dia. of spikes 08 mm.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	43.75	43.75
2	0.10	0.10	0.10	0.05	-0.10	2.50	46.25
3	0.16	0.14	0.05	0.05	-0.15	1.25	47.50
4	0.21	0.19	0.20	0.05	-0.20	3.75	51.25
5	0.36	0.34	0.35	0.15	-0.35	6.25	57.50
6	0.51	0.48	0.495	0.15	-0.50	3.75	61.25
7	0.66	0.64	0.65	0.15	-0.65	5.00	66.25
8	0.91	0.88	0.895	0.25	-0.90	5.00	71.25
9	1.26	1.24	1.25	0.35	-1.25	6.25	77.50
10	1.51	1.49	1.50	0.25	-1.50	3.75	81.25
11	1.76	1.74	1.75	0.25	-1.75	3.75	85.00
12	2.01	1.98	1.995	0.25	-2.00	1.25	86.25
13	2.26	2.24	2.25	0.25	-2.25	2.50	88.75
14	2.51	2.49	2.50	0.25	-2.50	2.50	91.25
15	2.76	2.74	2.75	0.25	-2.75	1.25	92.50
16	Cont. increase	Cont. increase	-	-	Continuous increase	zero	92.50

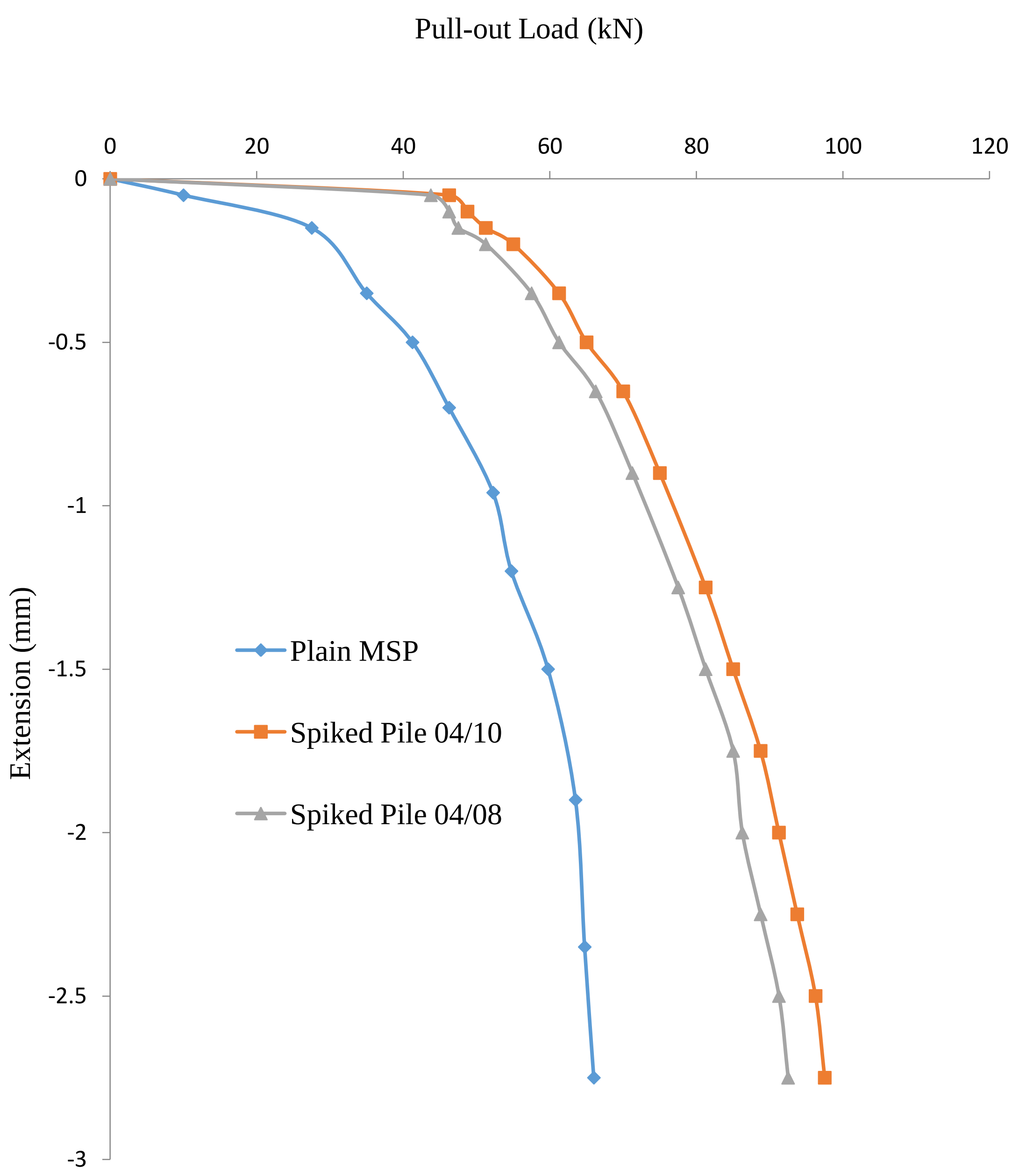
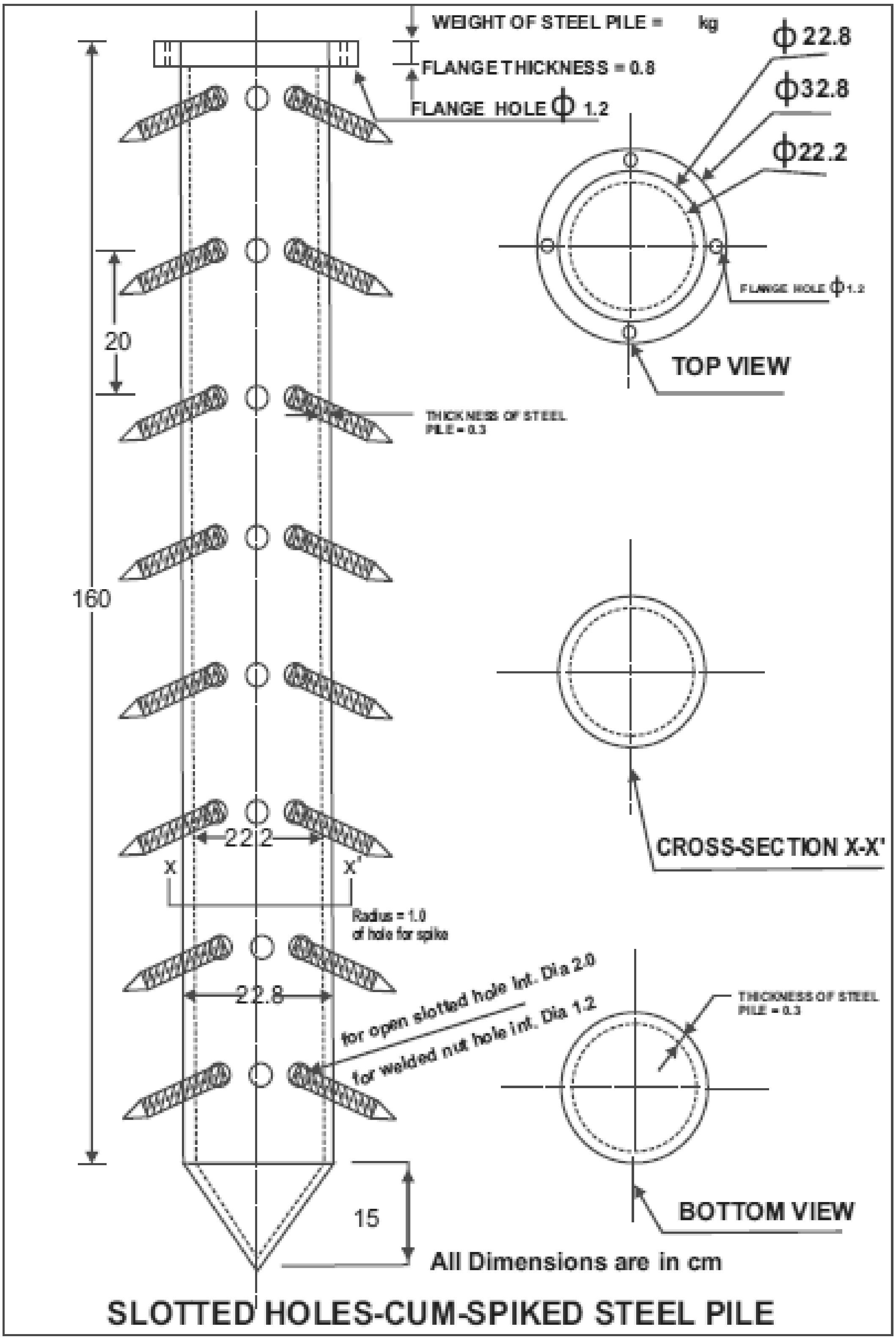


Figure 14: Comparison between side resistance of a plain model steel pile, a spiked model steel pile 04/08 and another spiked pile 04/10. Spiked pile 04/08- a spiked pile having spike length 04 cm and dia. of spike 08 mm at 90°**.** Spiked Pile 04/10- a spiked pile having spike length 04 cm and dia. of spike 10 mm at 90°**.**



Drawing 11. Spike of length 6.0 cm and dia. 8.0 mm through slotted holes at 90°. Weight of steel pile = 40.5 kg.

Table 14. Pull-out load vs. Extension for slotted holes-cum-spiked model steel pile. Spiked pile-06/08 i.e. a model steel pile having length of spikes 06 cm and dia. of spikes 08 mm.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.050	0.05	-0.05	61.25	61.25
2	0.10	0.10	0.100	0.05	-0.10	02.50	63.75
3	0.14	0.16	0.150	0.05	-0.15	3.75	67.50
4	0.18	0.21	0.195	0.05	-0.20	2.50	70.00
5	0.24	0.26	0.250	0.05	-0.25	1.25	71.25
6	0.34	0.36	0.350	0.10	-0.35	3.75	75.00
7	0.49	0.51	0.495	0.15	-0.50	5.00	80.00
8	0.74	0.76	0.750	0.25	-0.75	6.25	86.25
9	0.99	1.01	1.000	0.25	-1.00	5.00	91.25
10	1.23	1.26	1.245	0.25	-1.25	2.50	93.75
11	1.49	1.51	1.500	0.25	-1.50	1.25	95.00
12	1.74	1.76	1.750	0.25	-1.75	3.75	98.75
13	1.99	2.01	2.000	0.25	-2.00	1.25	100.00
14	2.24	2.26	2.25	0.25	-2.25	2.50	102.50
15	2.49	2.51	2.50	0.25	-2.50	1.25	103.75
16	2.74	2.76	2.75	0.25	-2.75	1.25	105.00
17	Cont. increase	Cont. increase	-	-	Continuous increase	zero	105.00

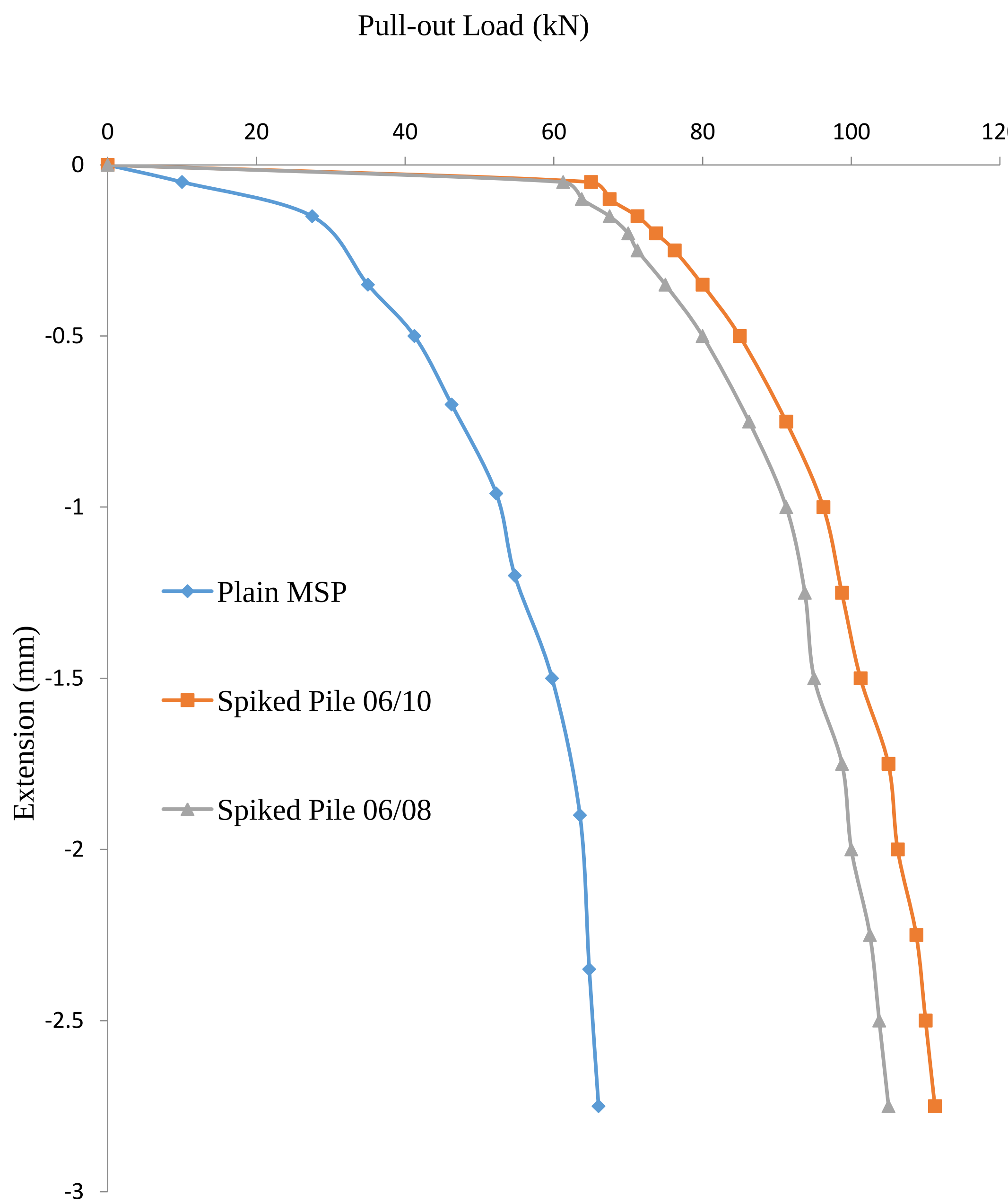
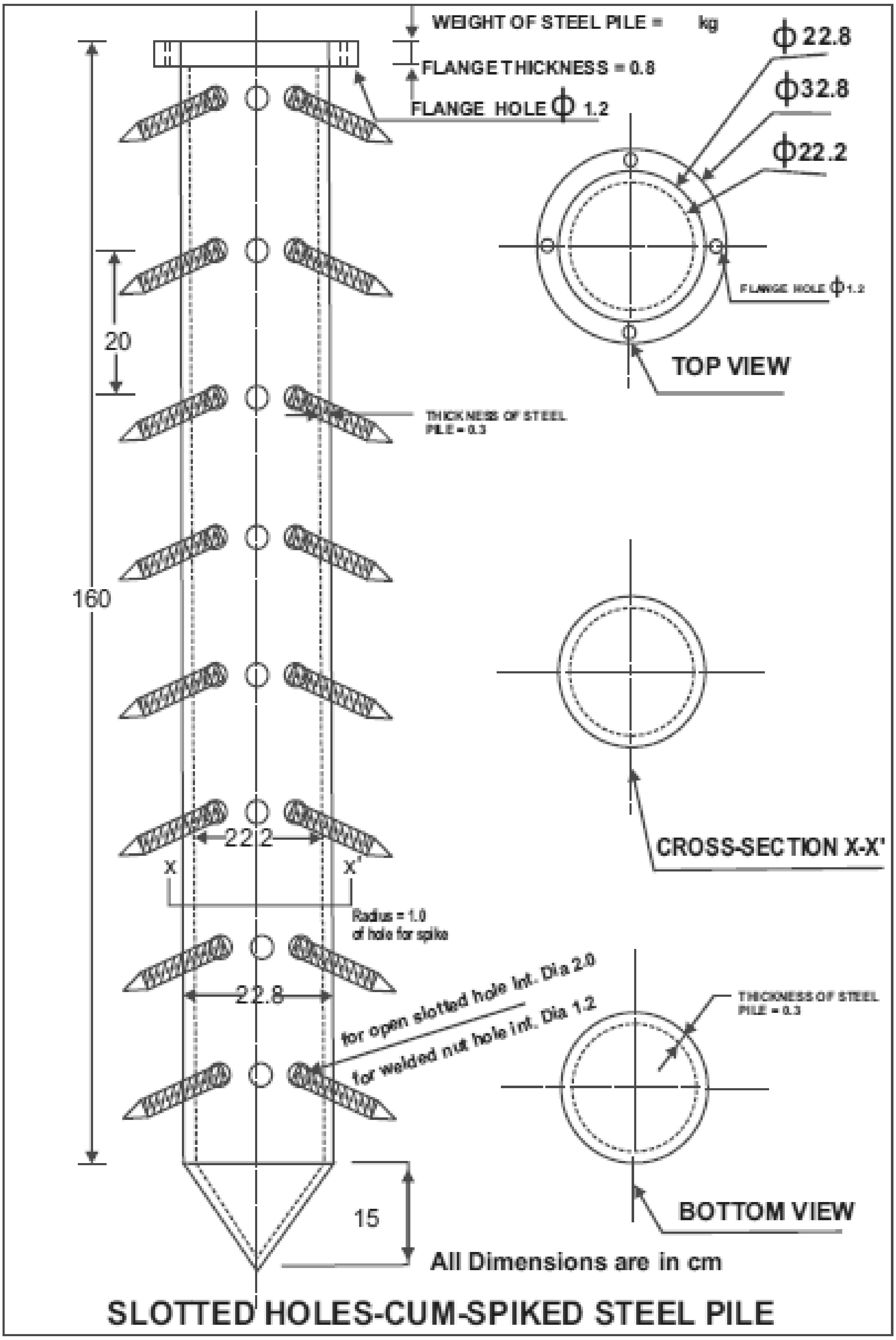


Figure 15: Comparison between side resistance of a plain model steel pile, a spiked model steel pile 06/08 and another spiked pile 06/10. Spiked pile 06/08- a spiked pile having spike length 06 cm and dia. of spike 08 mm at 90°**.** Spiked Pile 06/10- a spiked pile having spike length 06 cm and dia. of spike 10 mm at 90°.



Drawing 12. Spike of length 8.0 cm and dia. 8 mm through slotted holes at 90°. Weight of steel pile = 41.5 kg.

Table 15. Pull-out load vs. Extension for slotted holes-cum-spiked model steel pile. Spiked pile-08/08 i.e. a model steel pile having length of spikes 08 cm and dia. of spikes 08 mm.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	68.75	68.75
2	0.10	0.10	0.10	0.05	-0.10	10.00	78.75
3	0.16	0.14	0.15	0.05	-0.15	1.25	80.00
4	0.21	0.19	0.20	0.05	-0.20	2.50	82.50
5	0.26	0.24	0.25	0.05	-0.25	1.25	83.75
6	0.36	0.34	0.35	0.10	-0.35	2.50	86.25
7	0.51	0.49	0.50	0.15	-0.50	3.75	90.00
8	0.76	0.74	0.75	0.25	-0.75	6.25	96.25
9	1.01	0.99	1.00	0.25	-1.00	3.75	100.00
10	1.26	1.24	1.25	0.25	-1.25	3.75	103.75
11	1.51	1.49	1.50	0.25	-1.50	2.50	106.25
12	1.76	1.74	1.75	0.25	-1.75	2.50	108.75
13	2.01	1.99	2.00	0.25	-2.00	2.50	111.25
14	2.26	2.24	2.25	0.25	-2.25	1.25	112.50
15	2.51	2.49	2.50	0.25	-2.50	1.25	113.75
16	2.76	2.74	2.75	0.25	-2.75	1.25	115.00
17	Cont. increase	Cont. increase	-	-	Continuous increase	zero	115.00

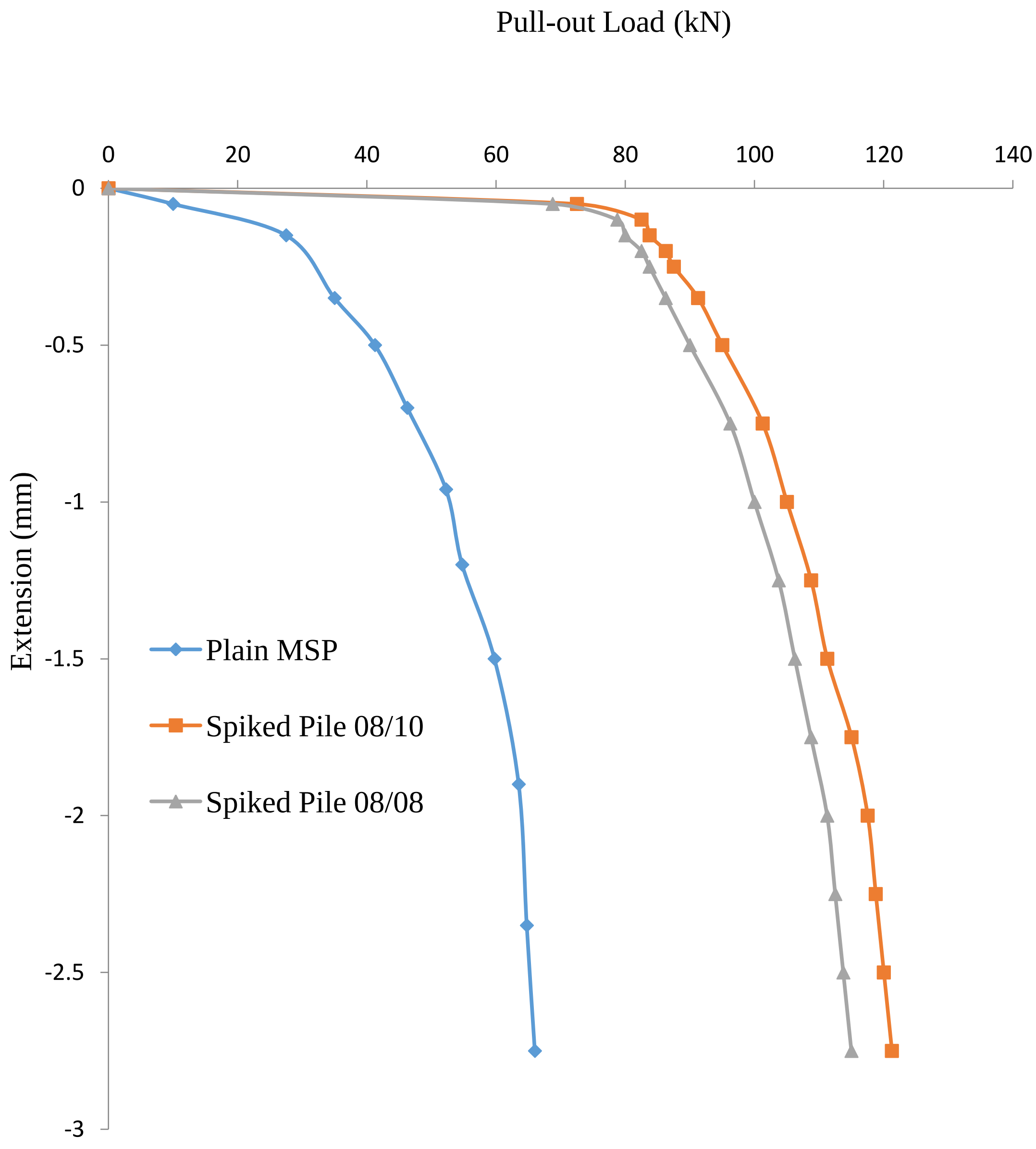
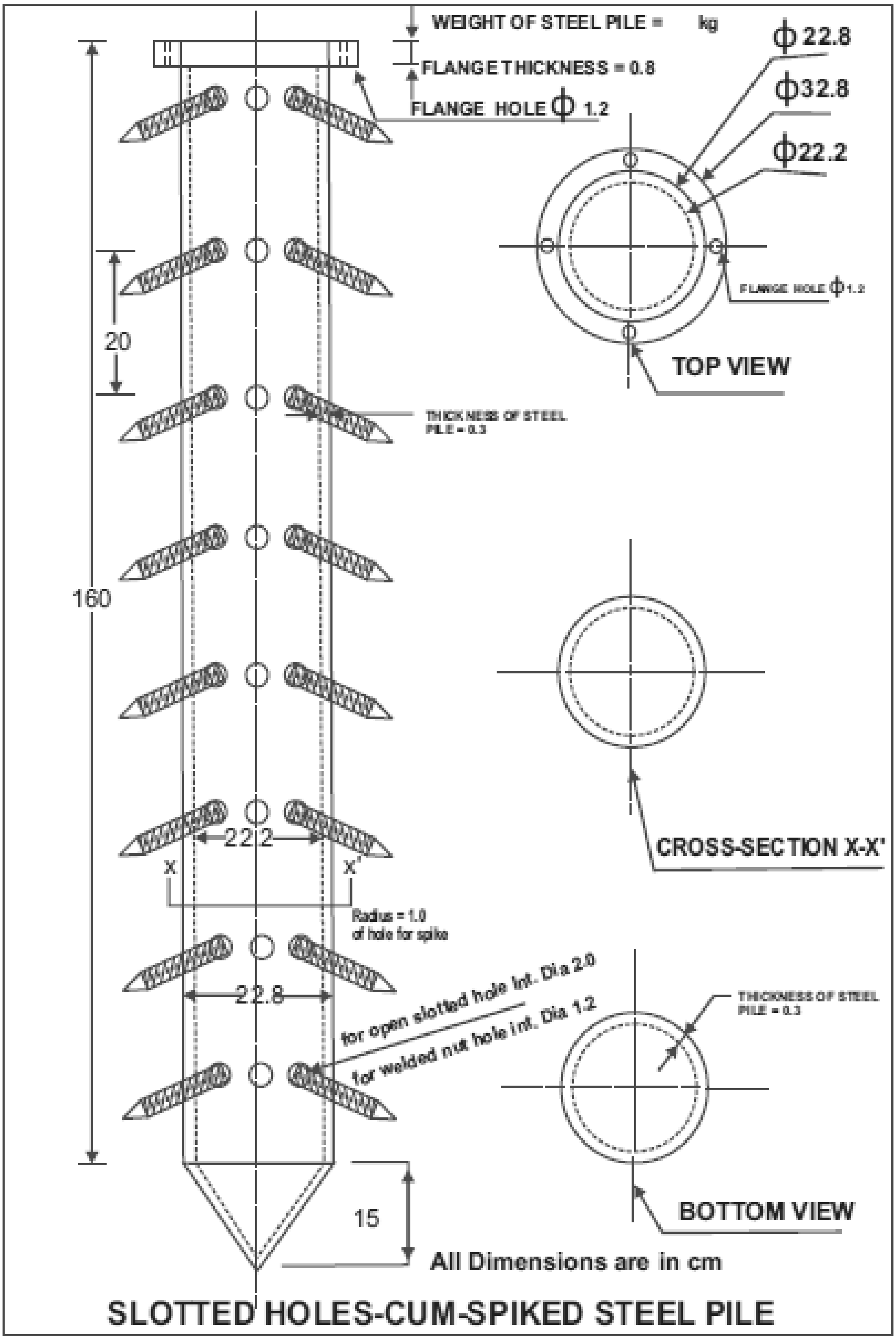


Figure 16: Comparison between side resistance of a plain model steel pile, a spiked model steel pile 08/08 and another spiked pile 08/10. Spiked Pile 08/08- a spiked pile having spike length 08 cm and dia. of spike 08 mm at90°. Spiked Pile 08/10- a spiked pile having spike length 08 cm and dia. of spike 10 mm at90°.



Drawing 13. Spike of length 10.0 cm and dia. 8 mm through slotted holes at 90°. Weight of steel pile=43.0 kg.

Table 16. Pull-out load vs. Extension for slotted holes-cum-spiked model steel pile. Spiked pile-10/08 i.e. a model steel pile having length of spikes 10 cm and dia. of spikes 08 mm.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	78.75	78.75
2	0.10	0.10	0.10	0.05	-0.10	08.75	87.50
3	0.14	0.16	0.15	0.05	-0.15	02.50	90.00
4	0.19	0.21	0.20	0.05	-0.20	02.50	92.50
5	0.24	0.26	0.25	0.05	-0.25	01.25	93.75
6	0.34	0.36	0.35	0.10	-0.35	2.50	96.25
7	0.49	0.51	0.50	0.15	-0.50	2.50	98.75
8	0.74	0.76	0.75	0.25	-0.75	5.00	103.75
9	0.99	1.01	1.00	0.25	-1.00	3.75	107.50
10	1.24	1.26	1.25	0.25	-1.25	3.75	111.25
11	1.49	1.51	1.50	0.25	-1.50	1.25	112.50
12	1.74	1.76	1.75	0.25	-1.75	2.50	115.00
13	1.99	2.01	2.00	0.25	-2.00	2.50	117.50
14	2.24	2.26	2.25	0.25	-2.25	1.25	118.75
15	2.49	2.51	2.50	0.25	-2.50	1.25	120.00
16	2.74	2.76	2.75	0.25	-2.75	1.25	121.25
17	Cont. increase	Cont. increase	-	-	Continuous increase	zero	121.25

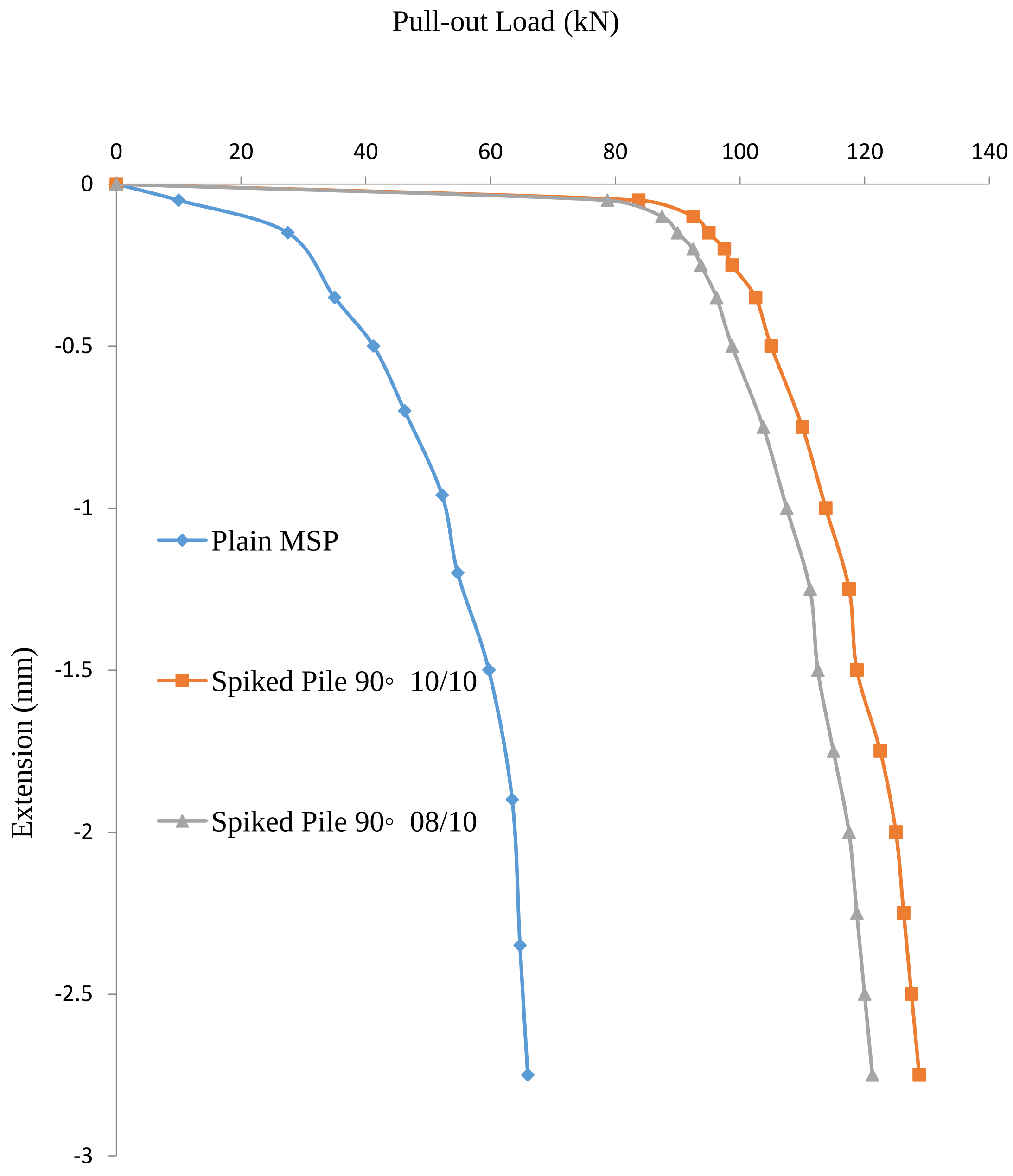
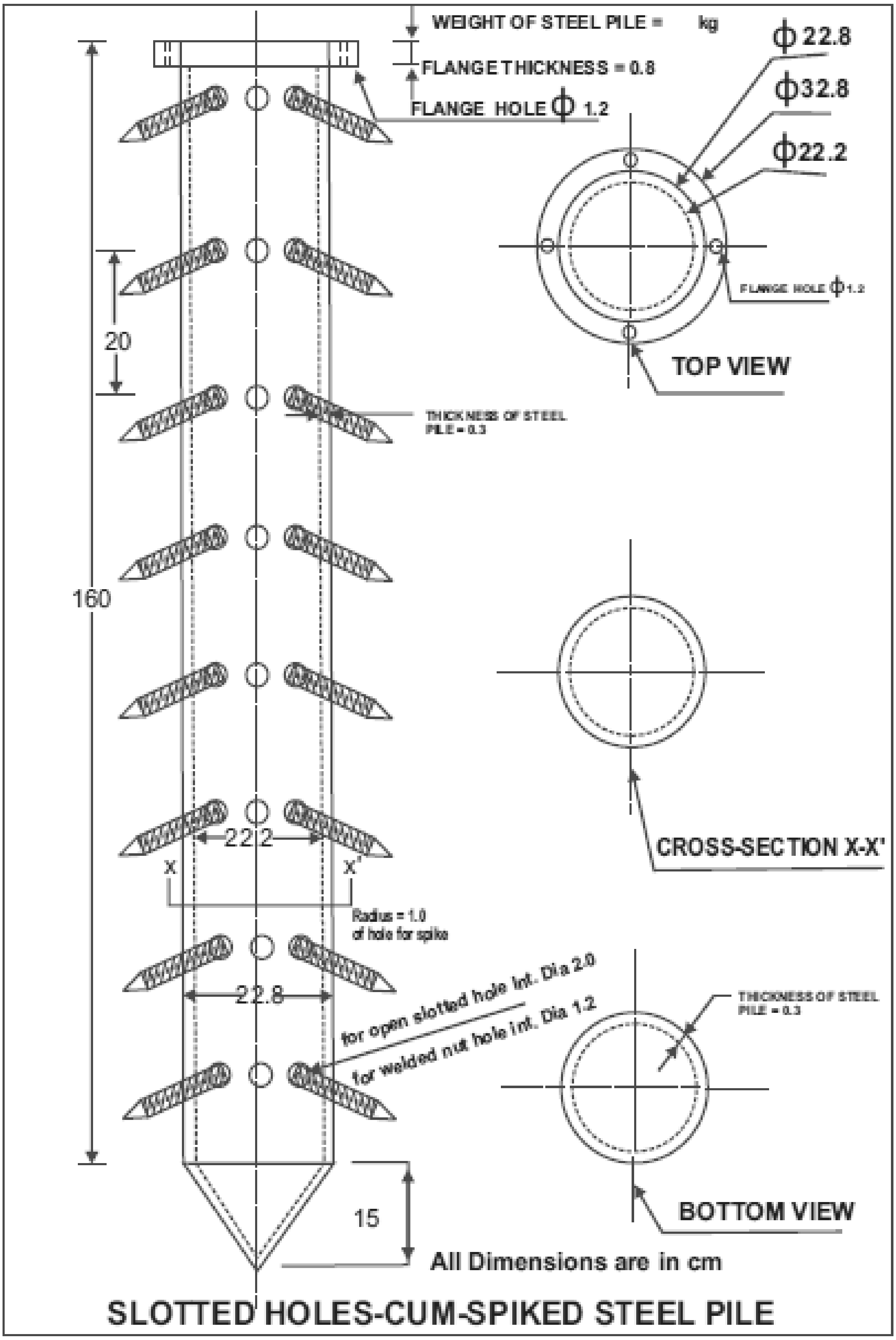


Figure 17: Comparison between side resistance of a plain model steel pile, a spiked model steel pile 10/08 and another spiked pile 10/10. Spiked Pile 10/08- a spiked pile having spike length 10 cm and dia. of spike 08 mm at 90°. Spiked pile 10/10- a spiked pile having spike length 10 cm and diameter of spike 10 mm at 90°.



Drawing 14. Slotted holes-cum-Inclined spikes of length 10.0 cm and dia. 10 mm at 30° inclination at a point w.r.t. positive direction of vertical plumb line. Weight of steel pile=46.0 kg.

Table 17. Pull-out load vs. Extension for slotted holes-cum-inclined spike model steel pile. An inclined spike model steel pile 30°-10/10 - a spiked pile having spike length 10 cm and dia. of spike 10 mm spiking out at 30° inclination at a point w.r.t. positive direction of vertical plumb line.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	62.50	62.50
2	0.10	0.10	0.10	0.05	-0.10	8.75	71.25
3	0.14	0.16	0.15	0.05	-0.15	2.50	73.75
4	0.19	0.21	0.20	0.05	-0.20	1.25	75.00
5	0.24	0.26	0.25	0.05	-0.25	1.25	76.25
6	0.34	0.36	0.35	0.10	-0.35	3.75	80.00
7	0.49	0.51	0.50	0.15	-0.50	1.25	81.25
8	0.74	0.76	0.75	0.25	-0.75	5.00	86.25
9	0.99	1.01	1.00	0.25	-1.00	3.75	90.00
10	1.24	1.26	1.25	0.25	-1.25	2.50	92.50
11	1.49	1.51	1.50	0.25	-1.50	1.25	93.75
12	1.74	1.76	1.75	0.25	-1.75	3.75	97.50
13	1.99	2.01	2.00	0.25	-2.00	1.25	98.75
14	2.24	2.26	2.25	0.25	-2.25	1.25	100.00
15	2.49	2.51	2.50	0.25	-2.50	1.25	101.25
16	2.74	2.76	2.75	0.25	-2.75	1.25	102.50
17	Cont. increase	Cont. increase	-	-	Continuous increase	zero	102.50

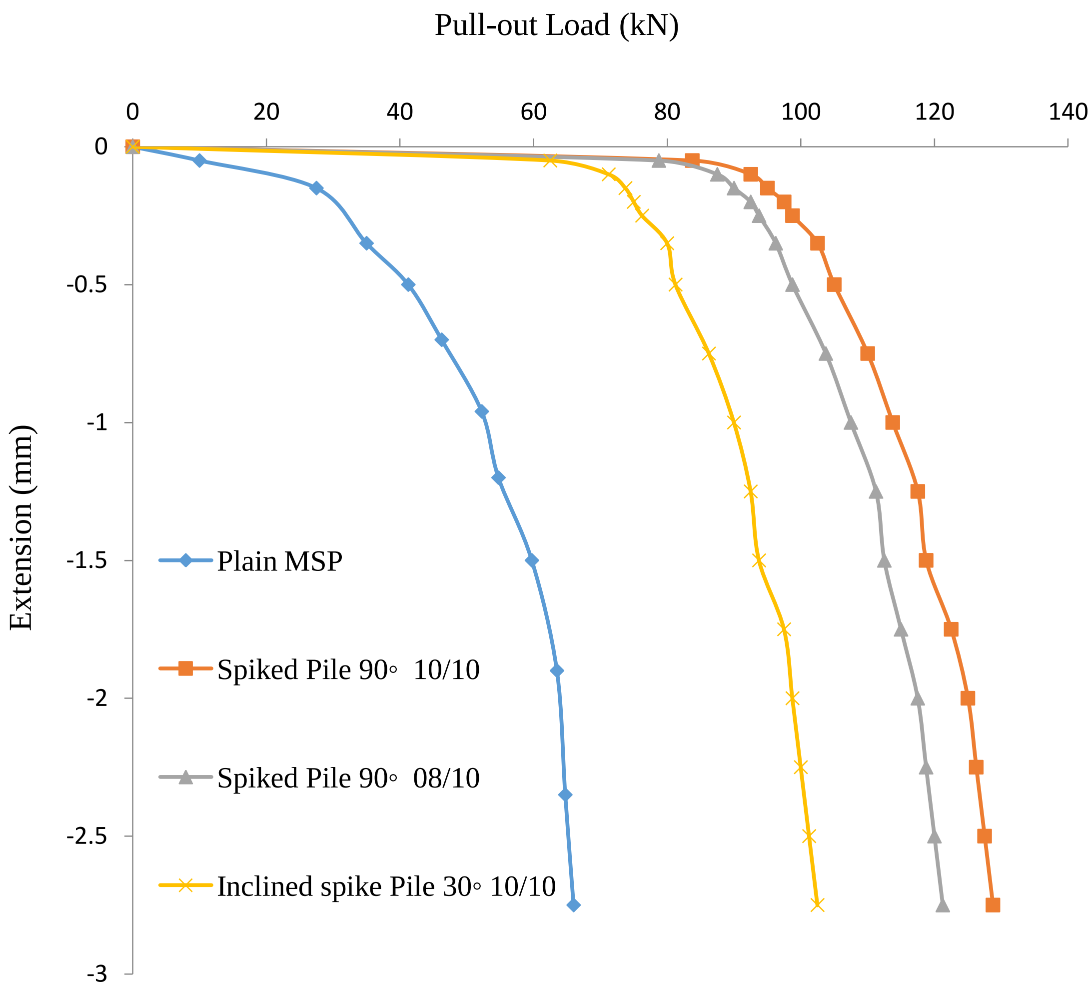
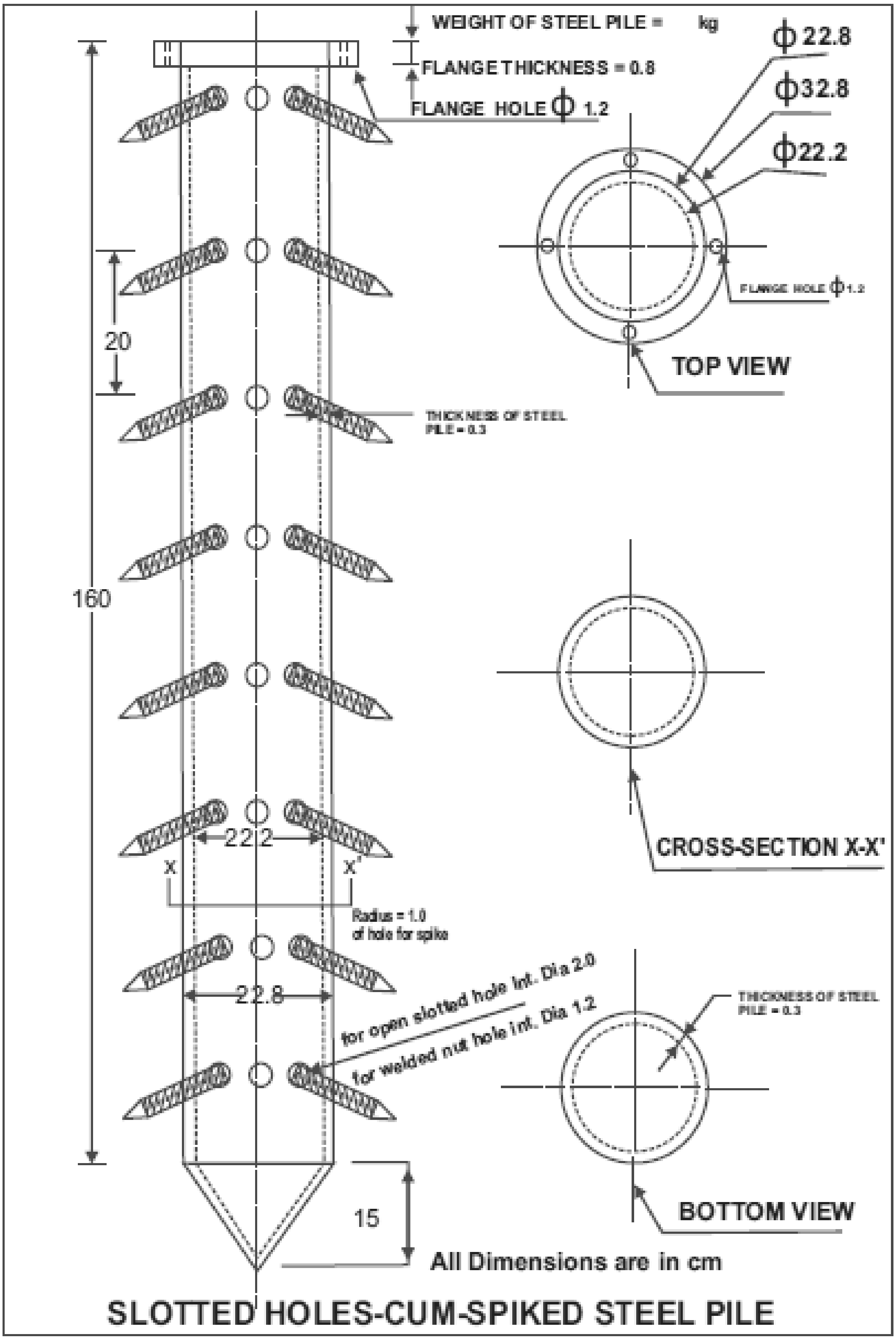


Figure 18: Comparison between side resistance of a plain model steel pile, a spiked model steel pile 90°-10/10, a spiked model steel pile 90°-08/10 and an inclined spike Pile 30°-10/10. A spiked model steel pile 90°-10/10- a spiked pile having spike length 10 cm and dia. of spike 10 mm, spiking out at 90°**.** A spiked model steel pile 90°-08/10 - a spiked pile having spike length 08 cm and dia. of spike 10 mm spiking out at 90°**.** An inclined spike model steel pile 30°-08/10-a spiked pile having spike length 08 cm and dia. of spike 10 mm spiking out at 30° inclination at a point w.r.t. positive direction of vertical plumb line.



Drawing 15. Slotted holes-cum-Inclined spikes of length 10.0 cm and dia. 10 mm at 60° inclination at a point w.r.t. positive direction of vertical plumb line. Weight of steel pile = 46.0 kg.

Table 18. Pull-out load vs. Extension for slotted holes-cum-inclined spike model steel pile. An inclined spike model steel pile 60°-10/10 - a spiked pile having spike length 10 cm and dia. of spike 10 mm spiking out at 60◦inclination at a point w.r.t. positive direction of vertical plumb line.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	91.25	91.25
2	0.10	0.10	0.10	0.05	-0.10	8.75	100.00
3	0.14	0.16	0.15	0.05	-0.15	1.25	101.25
4	0.19	0.21	0.20	0.05	-0.20	2.50	103.75
5	0.24	0.26	0.25	0.05	-0.25	1.25	105.00
6	0.34	0.36	0.35	0.10	-0.35	3.75	108.75
7	0.49	0.51	0.50	0.15	-0.50	2.50	111.25
8	0.74	0.76	0.75	0.25	-0.75	3.75	115.00
9	0.99	1.01	1.00	0.25	-1.00	3.75	118.75
10	1.24	1.26	1.25	0.25	-1.25	2.50	121.25
11	1.49	1.51	1.50	0.25	-1.50	1.25	122.50
12	1.74	1.76	1.75	0.25	-1.75	3.75	126.25
13	1.99	2.01	2.00	0.25	-2.00	1.25	127.50
14	2.24	2.26	2.25	0.25	-2.25	1.25	128.75
15	2.49	2.51	2.50	0.25	-2.50	1.25	130.00
16	2.74	2.76	2.75	0.25	-2.75	1.25	131.25
17	Cont. increase	Cont. increase	-	-	Continuous increase	zero	131.25

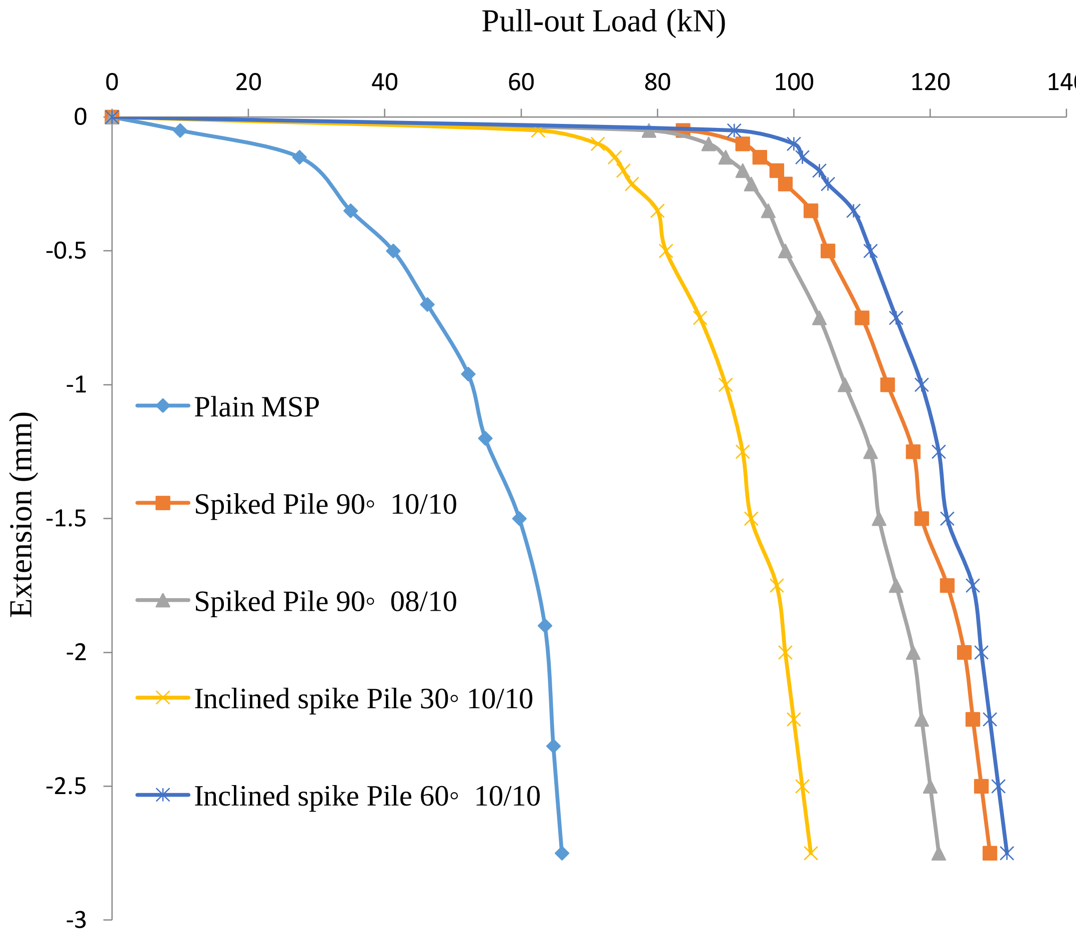
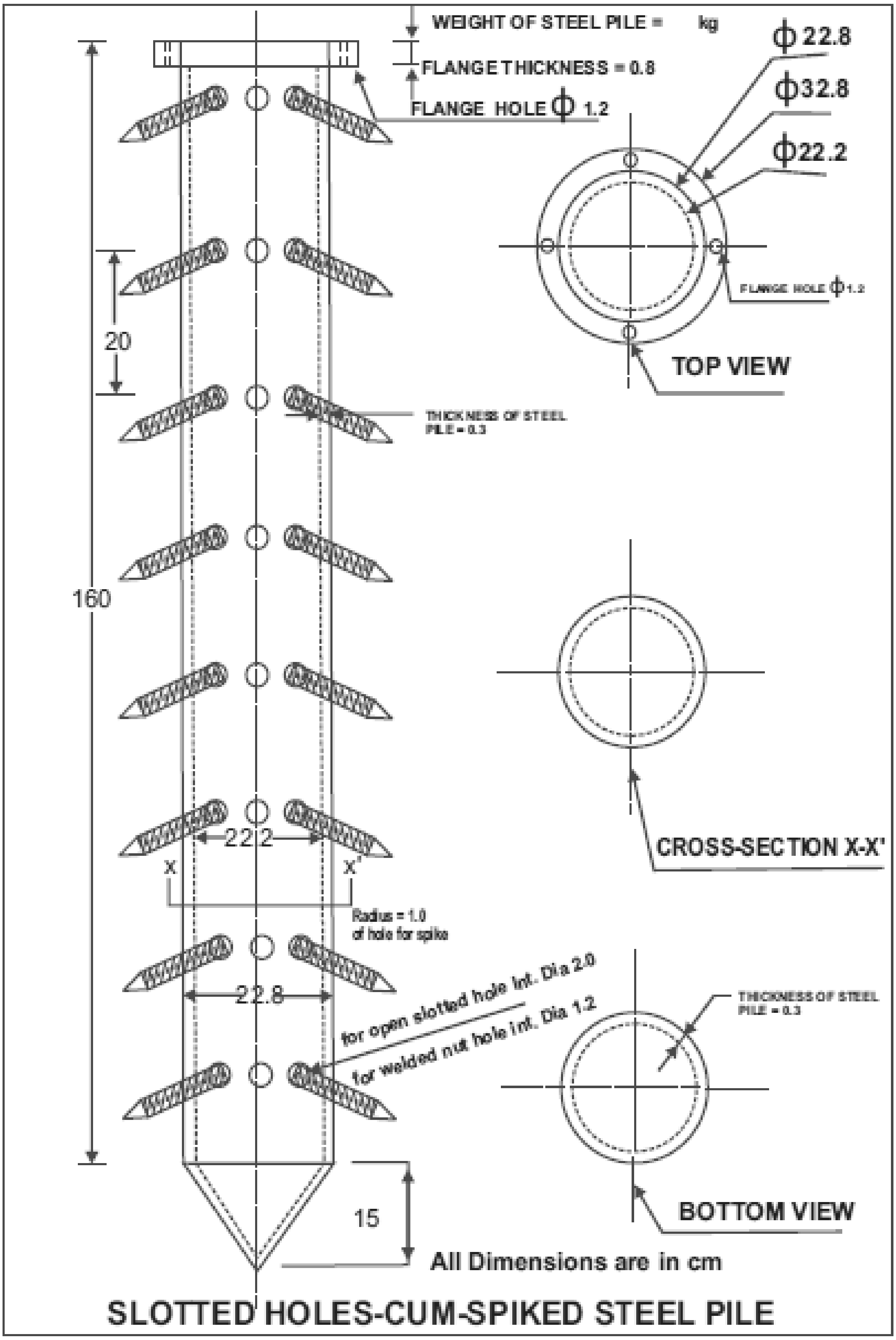


Figure 19: Comparison between side resistance of a plain model steel pile, a spiked model steel pile 90°-10/10, a spiked model steel pile 90°-08/10, an inclined spike Pile 30°-10/10 and an inclined spike Pile 60°-10/10. A spiked model steel pile 90°-10/10-a spiked pile having spike length 10 cm and dia. of spike 10 mm, spiking out at 90°**.** A spiked model steel pile 90°**-**08/10-a spiked pile having spike length 08 cm and dia. of spike 10 mm spiking out at90°**.**An inclined spike model steel pile 30°-10/10-a spiked pile having spike length 10 cm and dia. of spike 10 mm spiking out at 30° inclination at a point w.r.t. positive direction of vertical plumb line. An inclined spike model steel pile 60°-10/10 - a spiked pile having spike length 10 cm and dia. of spike 10 mm spiking out at 60° inclination at a point w.r.t. positive direction of vertical plumb line.



Drawing 16. Slotted holes-cum-Inclined spikes of length 10.0 cm and dia. 10 mm at approximate 90º inclination at a point w.r.t. positive direction of vertical plumb line. Weight of steel pile=46.0 kg.

Table 19. Pull-out load vs. Extension for slotted holes-cum-inclined spike model steel pile. An inclined spike model steel pile 90°-10/10-a spiked pile having spike length 10 cm and dia. of spike 10 mm spiking out at 90° inclination at a point w.r.t. positive direction of vertical plumb line.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	83.75	83.75
2	0.10	0.10	0.10	0.05	-0.10	08.75	92.50
3	0.14	0.16	0.15	0.05	-0.15	02.50	95.00
4	0.19	0.21	0.20	0.05	-0.20	02.50	97.50
5	0.24	0.26	0.25	0.05	-0.25	01.25	98.75
6	0.34	0.36	0.35	0.10	-0.35	3.75	102.50
7	0.49	0.51	0.50	0.15	-0.50	2.50	105.00
8	0.74	0.76	0.75	0.25	-0.75	5.00	110.00
9	0.99	1.01	1.00	0.25	-1.00	3.75	113.75
10	1.24	1.26	1.25	0.25	-1.25	3.75	117.50
11	1.49	1.51	1.50	0.25	-1.50	1.25	118.75
12	1.74	1.76	1.75	0.25	-1.75	3.75	122.50
13	1.99	2.01	2.00	0.25	-2.00	2.50	125.00
14	2.24	2.26	2.25	0.25	-2.25	1.25	126.25
15	2.49	2.51	2.50	0.25	-2.50	1.25	127.50
16	2.74	2.76	2.75	0.25	-2.75	1.25	128.75
17	Cont. increase	Cont. increase	-	-	Continuous increase	zero	128.75

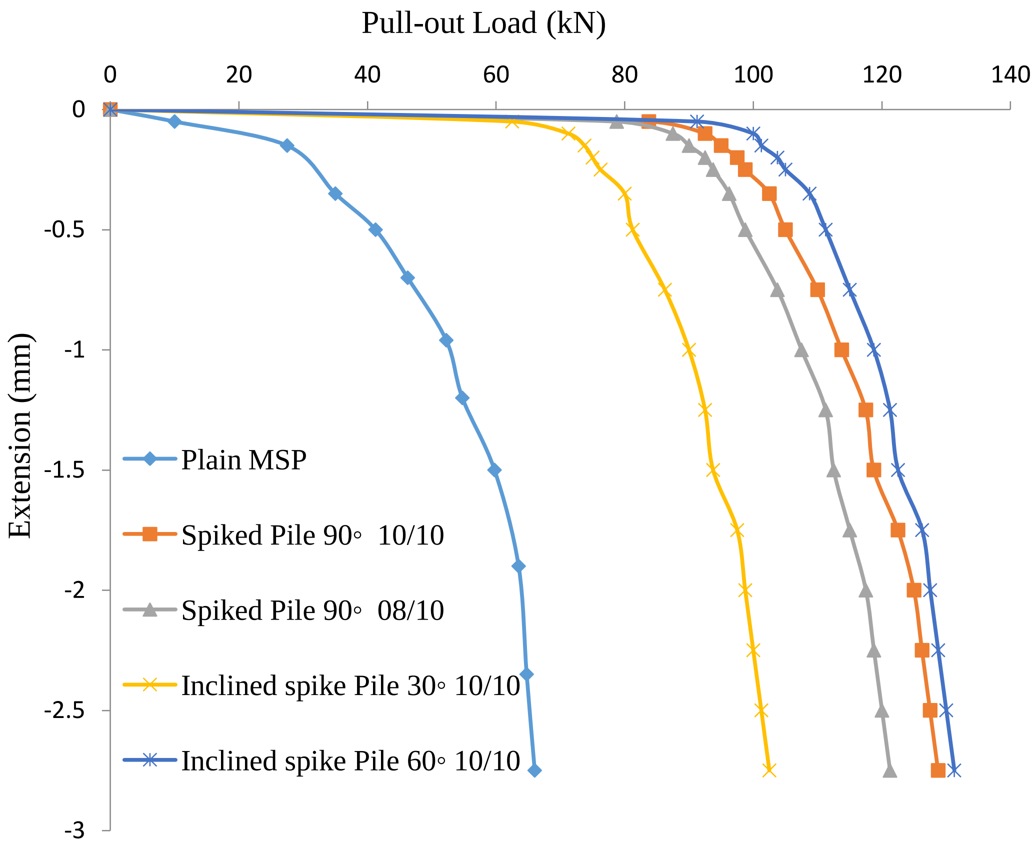
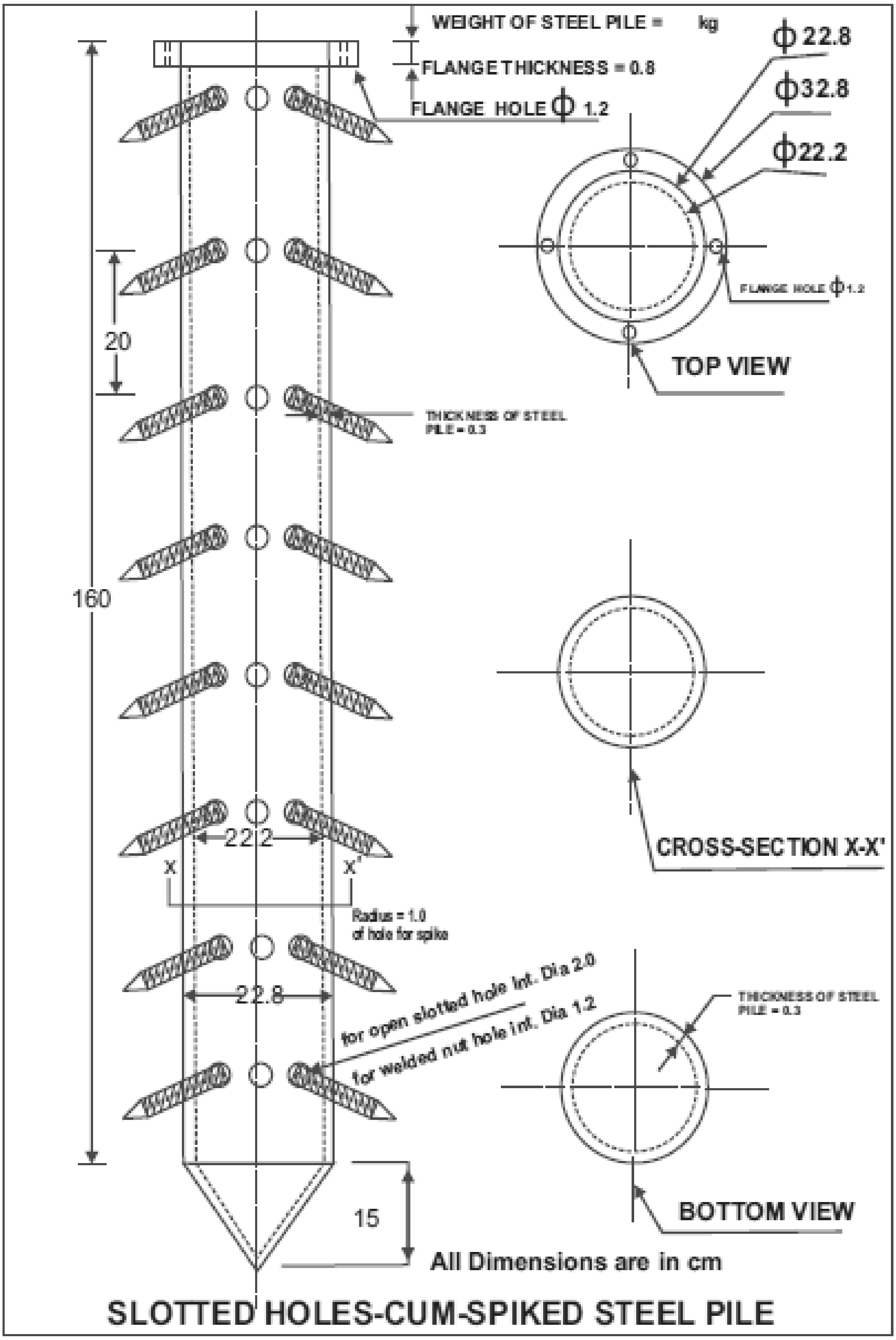


Figure 20: Comparison between side resistance of a plain model steel pile, a spiked model steel pile 90°-10/10, a spiked model steel pile 90°-08/10, an inclined spike Pile 30°-10/10 and an inclined spike Pile 60°-10/10. A spiked model steel pile 90°-10/10-a spiked pile having spike length 10 cm and dia. of spike 10 mm, spiking out at 90°**.** A spiked model steel pile 90°-08/10-a spiked pile having spike length 08 cm and dia. of spike 10 mm spiking out at90°**.**An inclined spike model steel pile 30°-10/10-a spiked pile having spike length 10 cm and dia. of spike 10 mm spiking out at 30°inclination at a point w.r.t. positive direction of vertical plumb line. An inclined spike model steel pile 60°-10/10-a spiked pile having spike length 10 cm and dia. of spike 10 mm spiking out at 60° inclination at a point w.r.t. positive direction of vertical plumb line.



Drawing 17. Slotted holes-cum-Inclined spikes of length 10.0 cm and dia. 10 mm at 120° inclination at a point w.r.t. positive direction of vertical plumb line. Weight of steel pile=46.0 kg.

Table 20. Pull-out load vs. Extension for slotted holes-cum-inclined spike model steel pile. An inclined spike model steel pile 120°-10/10-a spiked pile having spike length 10 cm and dia. of spike 10 mm spiking out at 120° inclination at a point w.r.t. positive direction of vertical plumb line.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	72.50	72.50
2	0.10	0.10	0.10	0.05	-0.10	7.50	80.00
3	0.14	0.16	0.15	0.05	-0.15	2.50	82.50
4	0.19	0.21	0.20	0.05	-0.20	2.50	85.00
5	0.24	0.26	0.25	0.05	-0.25	1.25	86.25
6	0.34	0.36	0.35	0.10	-0.35	2,50	88.75
7	0.49	0.51	0.50	0.15	-0.50	2.50	91.25
8	0.74	0.76	0.75	0.25	-0.75	5.00	96.25
9	0.99	1.01	1.00	0.25	-1.00	2.50	98.75
10	1.24	1.26	1.25	0.25	-1.25	3.75	102.50
11	1.49	1.51	1.50	0.25	-1.50	1.25	103.75
12	1.74	1.76	1.75	0.25	-1.75	2.50	106.25
13	1.99	2.01	2.00	0.25	-2.00	2.50	108.75
14	2.24	2.26	2.25	0.25	-2.25	1.25	110.00
15	2.49	2.51	2.50	0.25	-2.50	1.25	111.25
16	2.74	2.76	2.75	0.25	-2.75	1.25	112.50
17	Cont. increase	Cont. increase	-	-	Continuous increase	zero	112.50

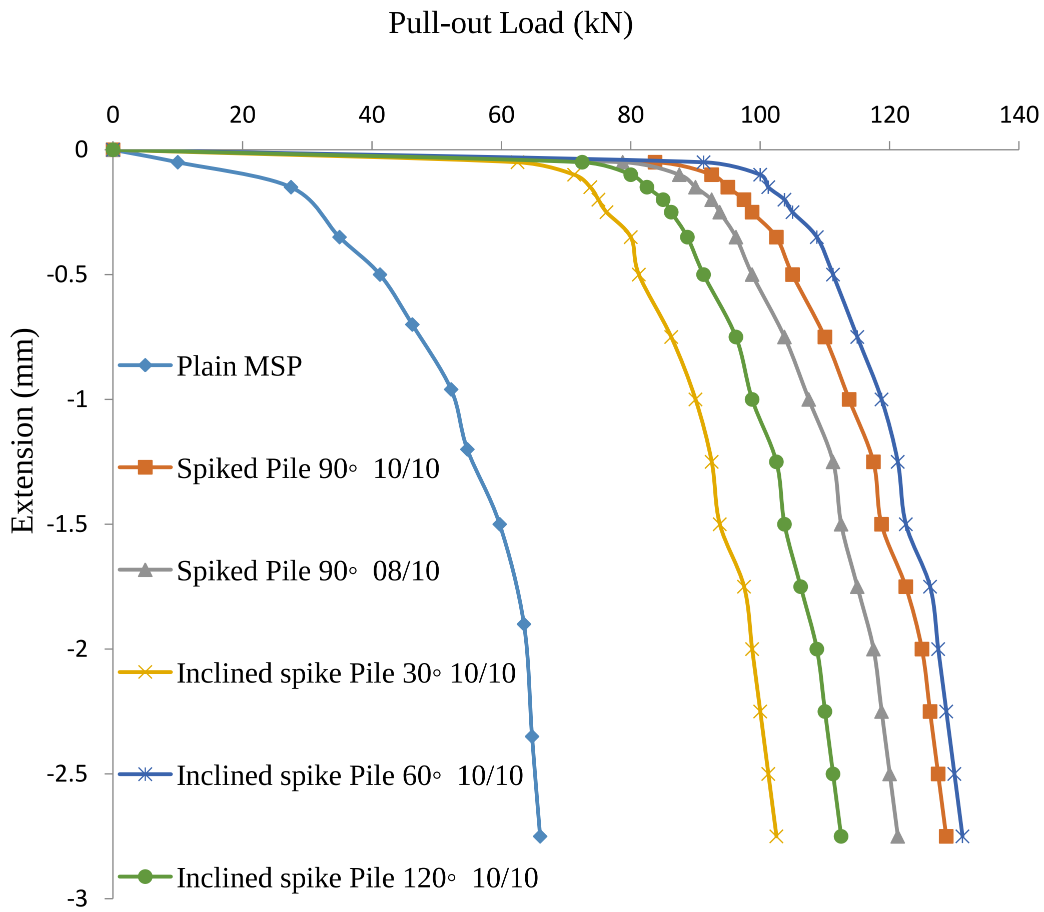
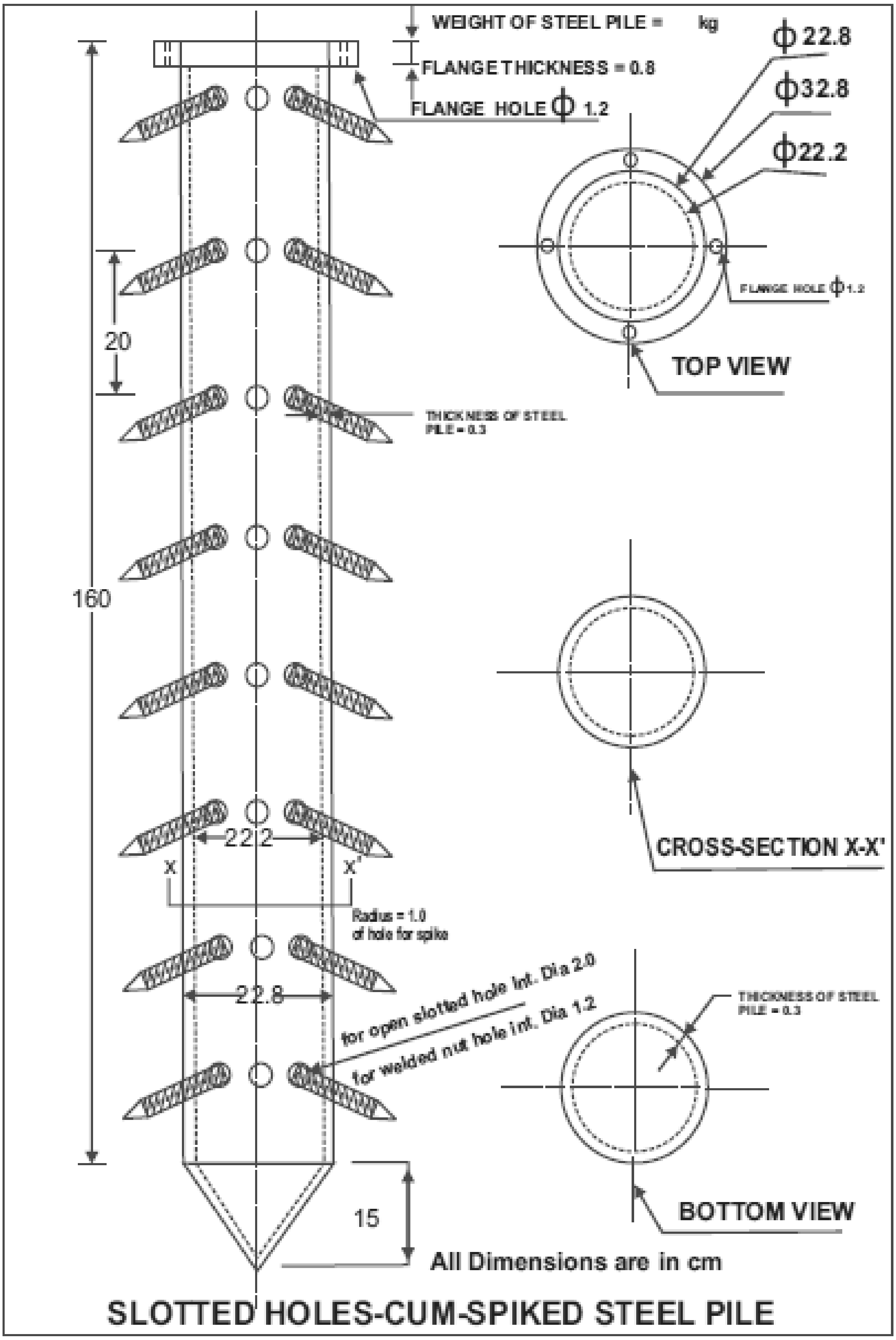


Figure 21: Comparison between side resistance of a plain model steel pile, a spiked model steel pile 90°-10/10, a spiked model steel pile 90°-08/10, an inclined spike Pile 30°-10/10,an inclined spike Pile 60°**-**10/10 and an inclined spike Pile 120°-10/10 A spiked model steel pile 90◦-10/10- a spiked pile having spike length 10 cm and dia. of spike 10 mm, spiking out at 90° inclination at a point w.r.t. positive direction of vertical plumb line **.** A spiked model steel pile 120°-10/10- a spiked pile having spike length 10 cm and dia. of spike 10 mm, spiking out at 120° inclination at a point w.r.t. positive direction of vertical plumb line. A spiked model steel pile 90°-08/10-a spiked pile having spike length 08 cm and dia. of spike 10 mm spiking out at90°inclination at a point w.r.t. positive direction of vertical plumb line**.** An inclined spike model steel pile 30°-10/10-a spiked pile having spike length 10 cm and dia. of spike 10 mm spiking out are 30° inclination at a point w.r.t. positive direction of vertical plumb line. An inclined spike model steel pile 60°-10/10-a spiked pile having spike length 10 cm and dia. of spike 10 mm spiking out at 60° inclination at a point w.r.t. positive direction of vertical plumb line.



Drawing 18. Slotted holes-cum-Inclined spikes of length 10.0 cm and dia. 10 mm at 150° inclination at a point w.r.t. positive direction of vertical plumb line. Weight of steel pile=46.0 kg.

Table 21. Pull-out load vs. Extension for slotted holes-cum-inclined spike model steel pile. An inclined spike model steel pile 150°-10/10-a spiked pile having spike length 10 cm and dia. of spike 10 mm spiking out at approximate 150° inclination at a point w.r.t. positive direction of vertical plumb line.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	53.75	53.75
2	0.10	0.10	0.10	0.05	-0.10	7.50	61.25
3	0.14	0.16	0.15	0.05	-0.15	2.50	63.75
4	0.19	0.21	0.20	0.05	-0.20	2.50	66.25
5	0.24	0.26	0.25	0.05	-0.25	2.50	68.75
6	0.34	0.36	0.35	0.10	-0.35	3.75	72.50
7	0.49	0.51	0.50	0.15	-0.50	2.50	75.00
8	0.74	0.76	0.75	0.25	-0.75	5.00	80.00
9	0.99	1.01	1.00	0.25	-1.00	3.75	83.75
10	1.24	1.26	1.25	0.25	-1.25	3.75	87.50
11	1.49	1.51	1.50	0.25	-1.50	3.75	91.25
12	1.74	1.76	1.75	0.25	-1.75	3.75	95.00
13	1.99	2.01	2.00	0.25	-2.00	2.50	97.50
14	2.24	2.26	2.25	0.25	-2.25	1.25	98.75
15	2.49	2.51	2.50	0.25	-2.50	1.25	100.00
16	2.74	2.76	2.75	0.25	-2.75	1.25	101.25
18	Cont. increase	Cont. increase	-	-	Continuous increase	zero	101.25

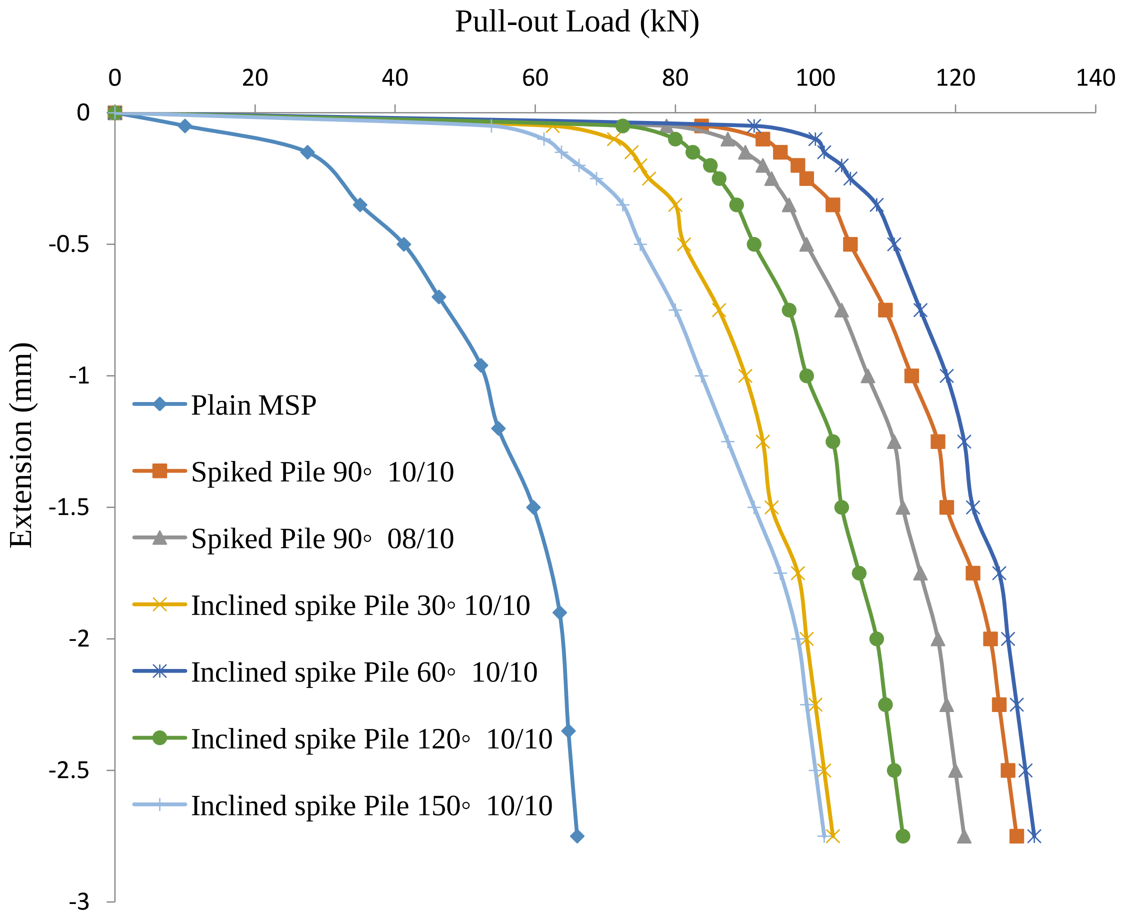
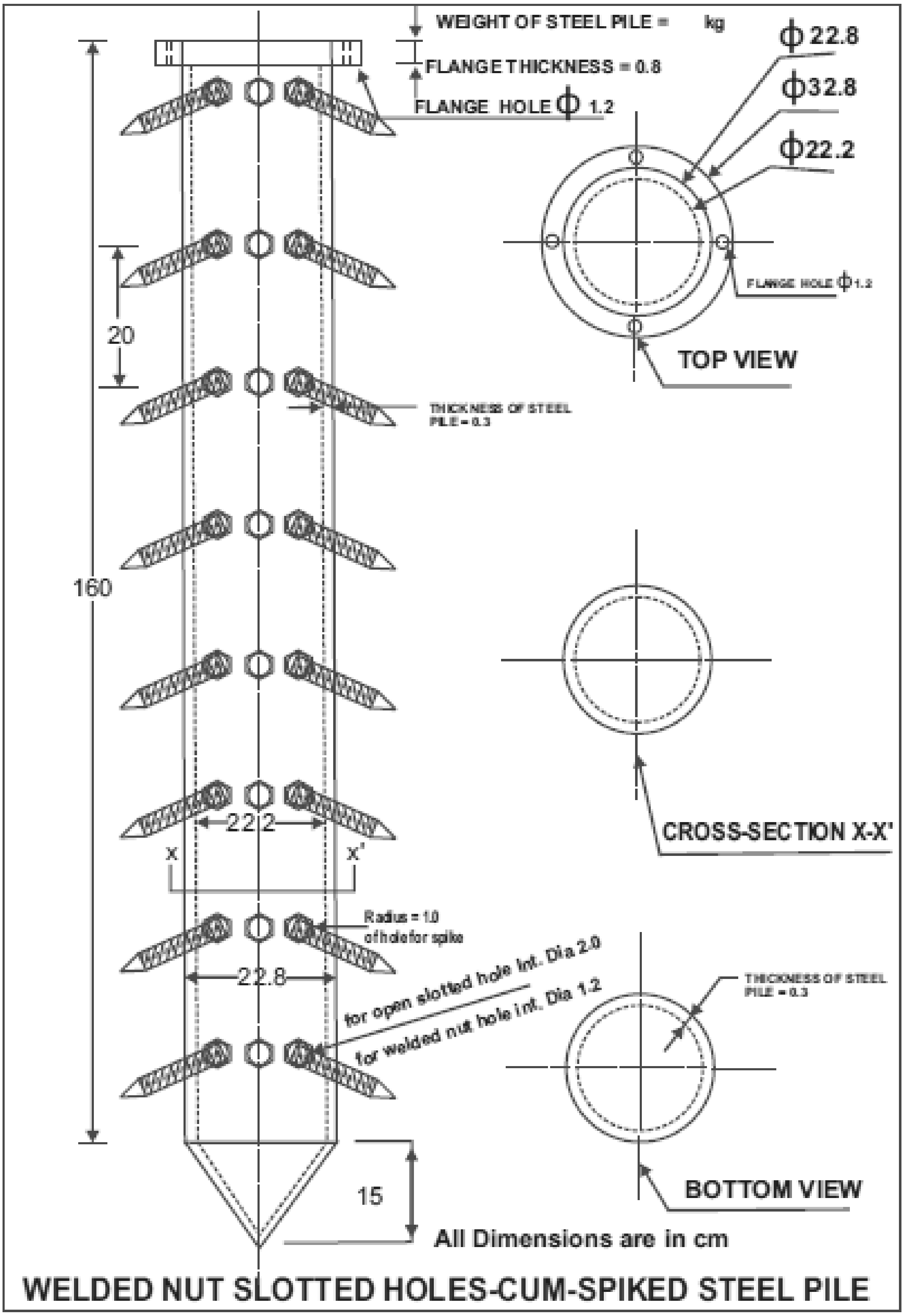


Figure 22: Comparison between side resistance of a plain model steel pile, a spiked model steel pile 90°-10/10, a spiked model steel pile 90°-08/10, an inclined spike pile 30°-10/10, an inclined spike pile 60°-10/10, an inclined spike Pile 120°-10/10 and an inclined spike Pile 150°-10/10. A spiked model steel pile 90°-10/10- a spiked pile having spike length 10 cm and dia. of spike 10 mm, spiking out at 90° inclination at a point w.r.t. positive direction of vertical plumb line. A spiked model steel pile 120°-10/10- a spiked pile having spike length 10 cm and dia. of spike 10 mm, spiking out at 120° inclination at a point w.r.t. positive direction of vertical plumb line. A spiked model steel pile 90°-08/10-a spiked pile having spike length 08 cm and dia. of spike 10 mm spiking out at90°inclination at a point w.r.t. positive direction of vertical plumb line. An inclined spike model steel pile 30°-10/10-a spiked pile having spike length 10 cm and dia. of spike 10 mm spiking out at 30°inclination at a point w.r.t. positive direction of vertical plumb line. An inclined spike model steel pile 60°-10/10- a spiked pile having spike length 10 cm and dia. of spike 10 mm spiking out at 60° inclination at a point w.r.t. positive direction of vertical plumb line. A spiked model steel pile 150°-10/10- a spiked pile having spike length 10 cm and dia. of spike 10 mm, spiking out at 150° inclination at a point w.r.t. positive direction of plumb.



Drawing 19. Spike of length 10.0 cm and dia. 10 cm through slotted hole inclined at exactly 90◦ (orthogonal direction).Weight of steel pile = 46kg

Table 22. Pull-out load vs. Extension for welded nuts slotted holes-cum-spiked model steel pile 90°-10/10 - a spiked pile having spike length 10 cm and dia. of spike 10 mm spiking out at exactly 90° inclination at a point w.r.t. positive direction of vertical plumb line.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	91.25	91.25
2	0.10	0.10	0.10	0.05	-0.10	7.50	98.75
3	0.14	0.16	0.15	0.05	-0.15	2.50	101.25
4	0.19	0.21	0.20	0.05	-0.20	2.50	103.75
5	0.24	0.26	0.25	0.05	-0.25	2,50	106.25
6	0.34	0.36	0.35	0.10	-0.35	3.75	110.00
7	0.49	0.51	0.50	0.15	-0.50	3.75	105.00
8	0.74	0.76	0.75	0.25	-0.75	5.00	110.00
9	0.99	1.01	1.00	0.25	-1.00	3.75	113.75
10	1.24	1.26	1.25	0.25	-1.25	5.00	118.75
11	1.49	1.51	1.50	0.25	-1.50	1.25	120.00
12	1.74	1.76	1.75	0.25	-1.75	3.75	123.75
13	1.99	2.01	2.00	0.25	-2.00	2.50	126.25
14	2.24	2.26	2.25	0.25	-2.25	2.50	128.75
15	2.49	2.51	2.50	0.25	-2.50	1.25	130.00
16	2.74	2.76	2.75	0.25	-2.75	1.25	131.25
18	Cont. increase	Cont. increase	-	-	Continuous increase	zero	131.25

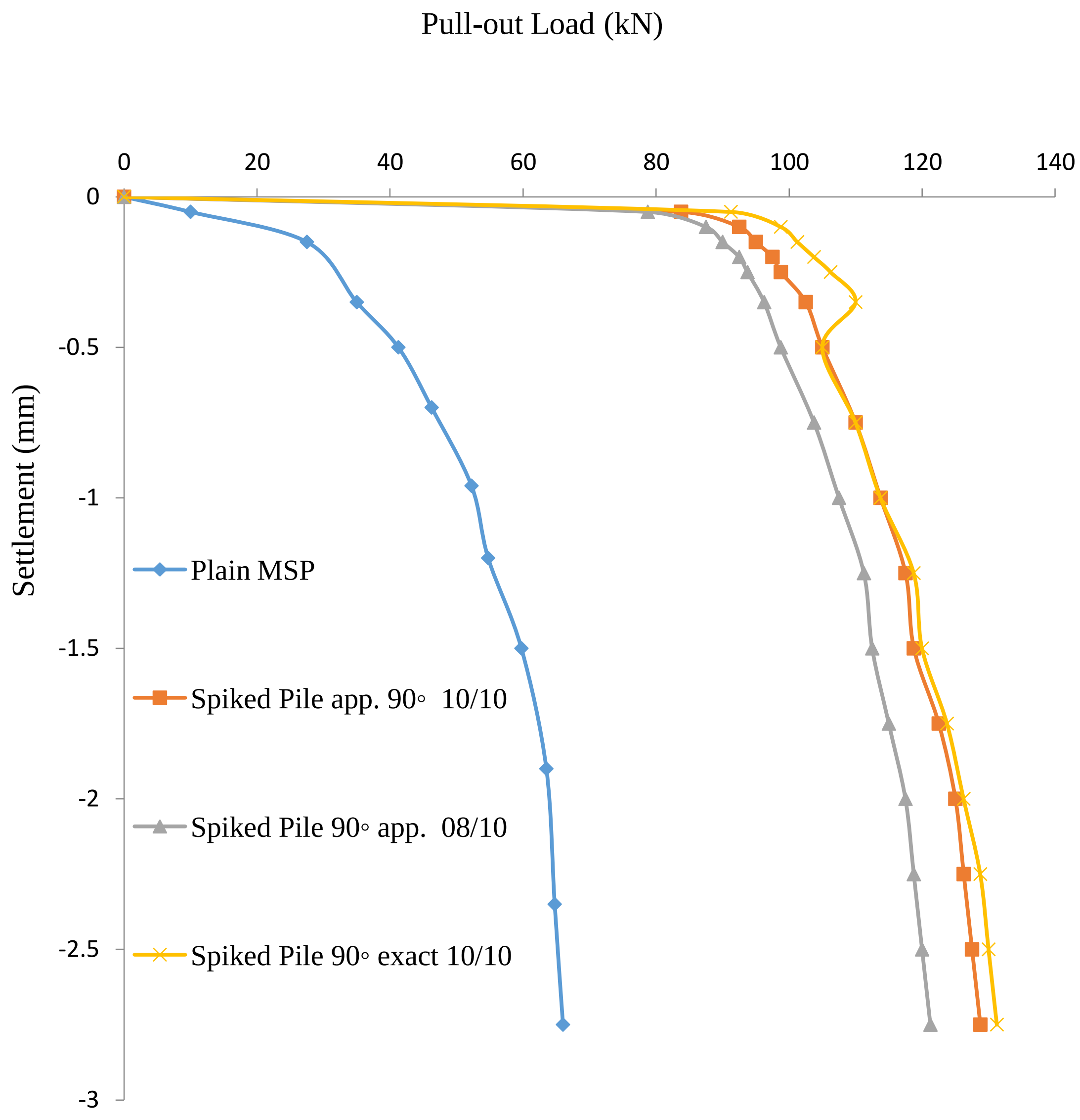
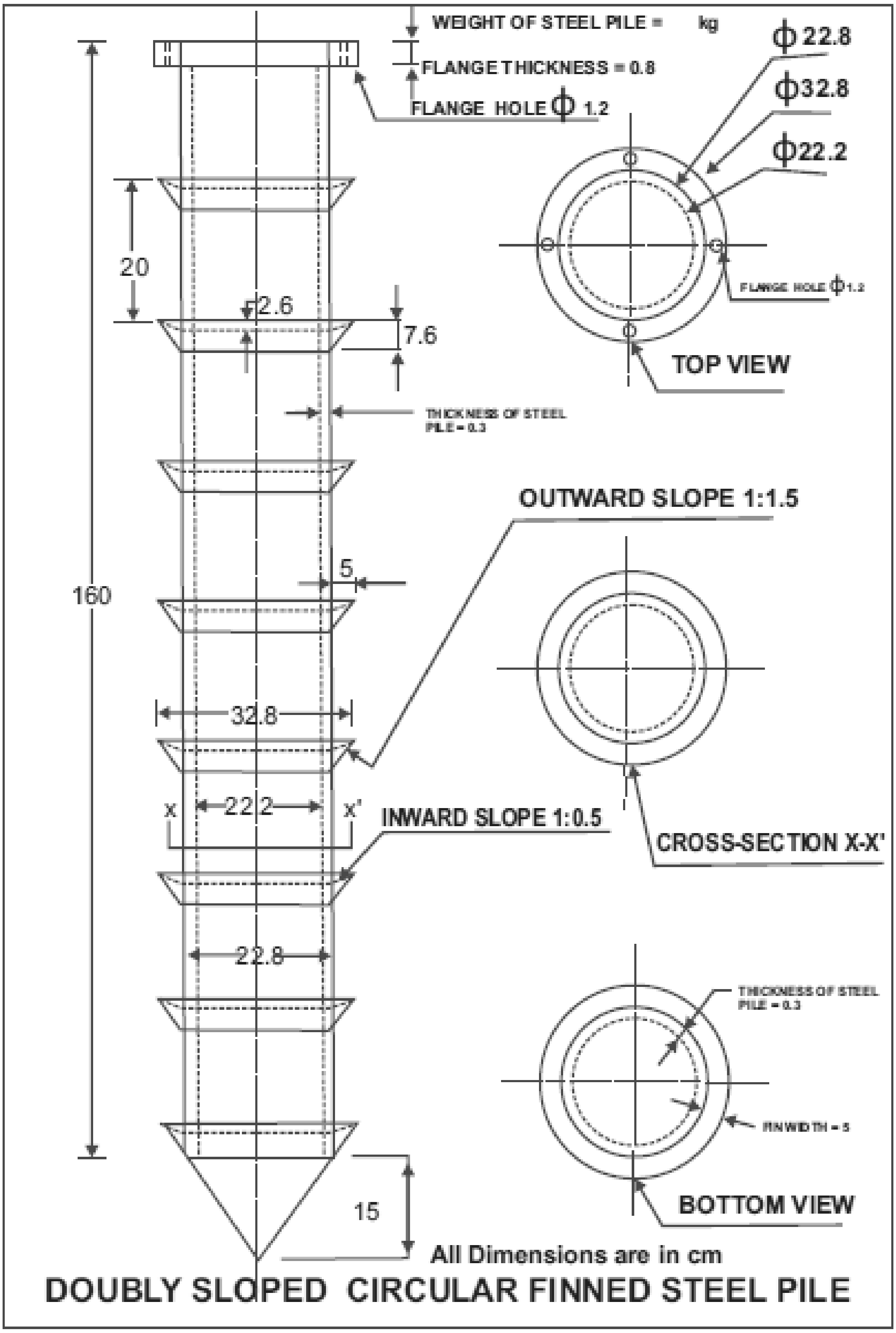


Figure 23: Comparison between side resistances of plain MSP, one spiked MSP - spike of length 10 cm and dia. 08 mm at approximate 90° i.e. +/- 5◦ and two spiked pile's having spikes of length 10 cm and dia. 10 mm at approximate 90° i.e. +/- 5◦ and exactly at 90◦respectively.



Drawing 20: Doubly sloped circular finned (faced vertically upwards) steel pile with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals; Weight of steel pile=46.7kg.

Table 23. Pull-out load vs. Extension for Doubly sloped circular finned (faced vertically upwards) model steel pile with circular fins. In its first test, dry sand was not added manually in between the fins while the steel pile was being driven inside the dry sand. Its detailed specifications are mentioned on previous page.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	51.25	51.25
2	0.10	0.10	0.10	0.05	-0.10	5.00	56.25
3	0.16	0.14	0.15	0.05	-0.15	2.50	58.75
4	0.21	0.19	0.20	0.05	-0.20	1.25	60.00
5	0.26	0.24	0.25	0.05	-0.25	2.50	62.50
6	0.36	0.34	0.35	0.10	-0.35	2.50	65.00
7	0.51	0.49	0.50	0.15	-0.50	5.00	70.00
8	0.76	0.74	0.75	0.25	-0.75	5.00	75.00
9	1.01	0.99	1.00	0.25	-1.00	7.50	82.50
10	1.26	1.24	1.25	0.25	-1.25	5.00	87.50
11	1.51	1.49	1.50	0.25	-1.50	3.75	91.25
12	1.76	1.74	1.75	0.25	-1.75	3.75	95.00
13	2.01	1.99	2.00	0.25	-2.00	2.50	97.50
14	2.26	2.24	2.25	0.25	-2.25	3.75	101.25
15	2.51	2.49	2.50	0.25	-2.50	2.50	103.75
16	2.76	2.74	2.75	0.25	-2.75	1.25	105.00
17	3.01	2.99	3.00	0.25	-3.00	1.25	106.25
18	Cont. increase	Cont. increase	-	-	Continuous increase	zero	106.25

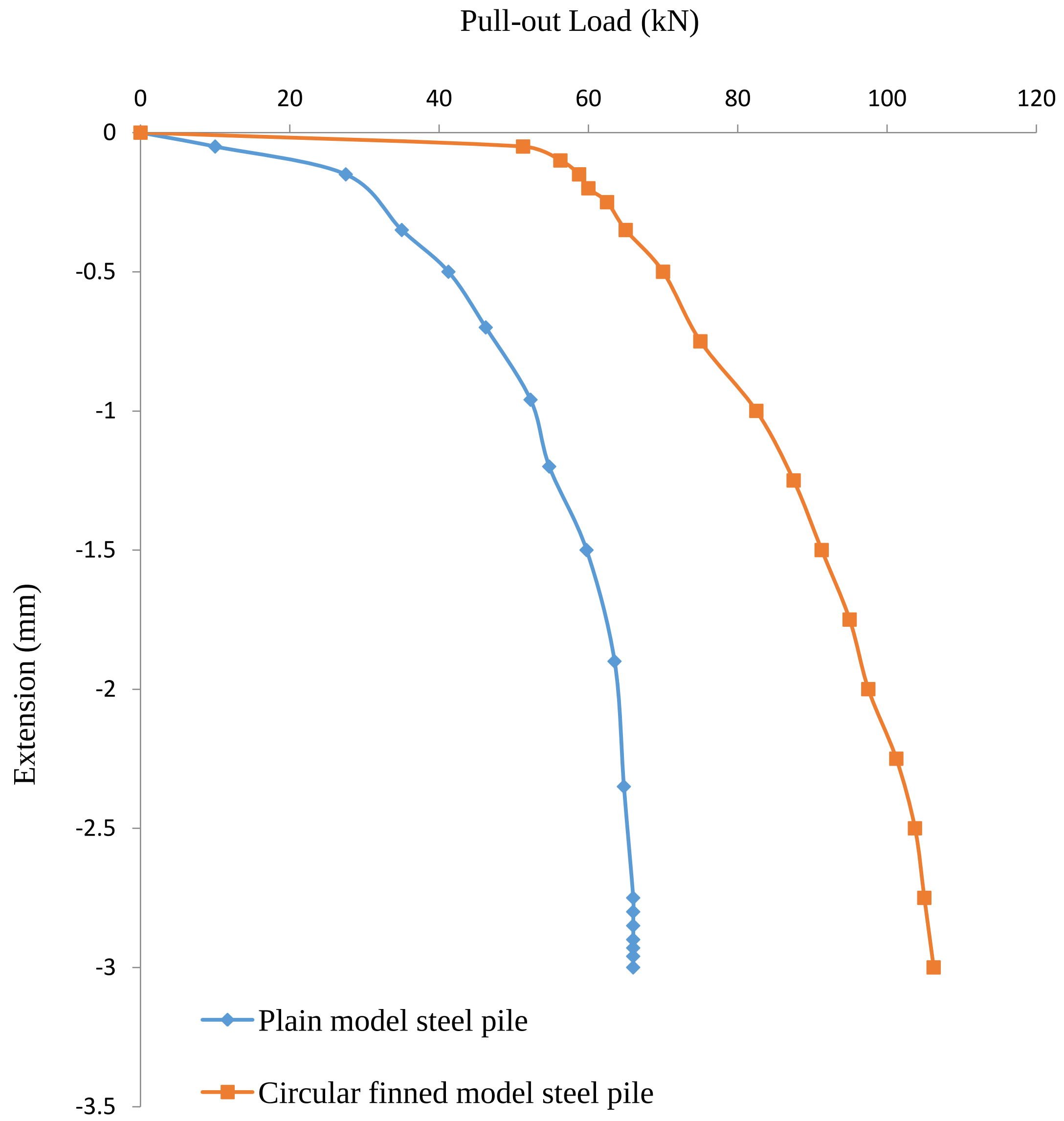
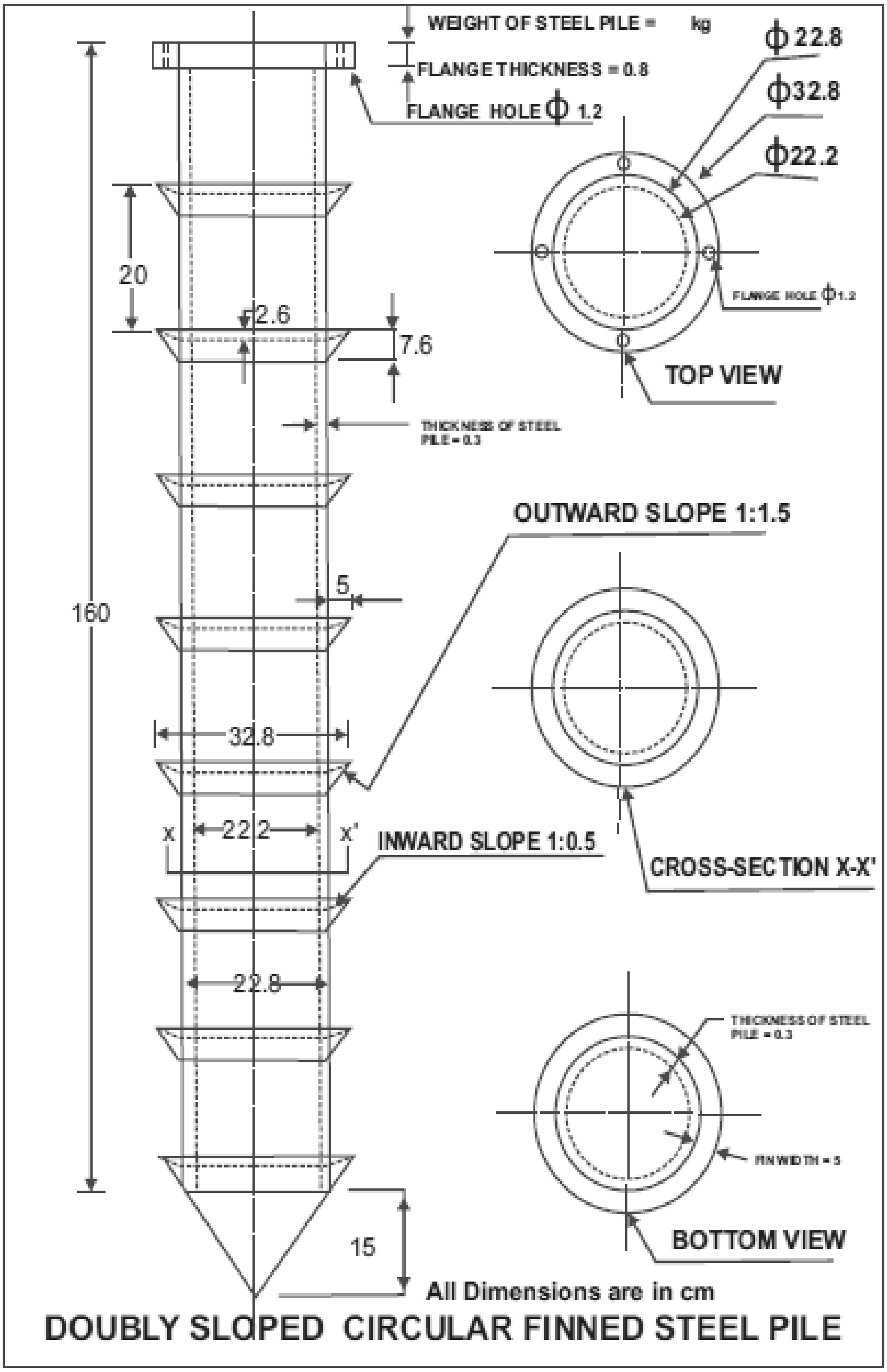


Figure 24: Graph showing comparison between side resistances for Pull-out load vs. Extension for doubly sloped circular finned (faced vertically upwards) model steel pile with circular fins. In its second test, dry sand was not added manually in between the fins while the steel pile was being driven inside the dry sand.



Drawing 21. Doubly sloped circular finned (faced vertically upwards) steel pile with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals; Weight of steel pile=46.7kg. In its second test, dry sand was added and manually compacted in between the fins while the steel pile was being driven inside the dry sand.

Table 24. Pull-out load vs. Extension for Doubly sloped circular finned (faced vertically upwards) model steel pile with circular fins. In its second test, dry sand was added and manually compacted in between the fins while the steel pile was being driven inside the dry sand.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	97.50	97.50
2	0.10	0.10	0.10	0.05	-0.10	7.50	105.00
3	0.16	0.14	0.15	0.05	-0.15	3.75	108.75
4	0.21	0.19	0.20	0.05	-0.20	3.75	112.50
5	0.26	0.24	0.25	0.05	-0.25	1.25	113.75
6	0.36	0.34	0.35	0.10	-0.35	5.00	118.75
7	0.51	0.49	0.50	0.15	-0.50	3.75	122.50
8	0.76	0.74	0.75	0.25	-0.75	6.25	128.75
9	1.01	0.99	1.00	0.25	-1.00	5.00	133.75
10	1.26	1.24	1.25	0.25	-1.25	3.75	137.50
11	1.51	1.49	1.50	0.25	-1.50	3.75	141.25
12	1.76	1.74	1.75	0.25	-1.75	1.25	142.50
13	2.01	1.99	2.00	0.25	-2.00	2.50	145.00
14	2.26	2.24	2.25	0.25	-2.25	1.25	146.25
15	2.51	2.49	2.50	0.25	-2.50	1.25	147.50
16	2.76	2.74	2.75	0.25	-2.75	1.25	148.75
17	3.01	2.99	3.00	0.25	-3.00	1.25	150.00
18	Cont. increase	Cont. increase	-	-	Continuous increase	zero	150.00

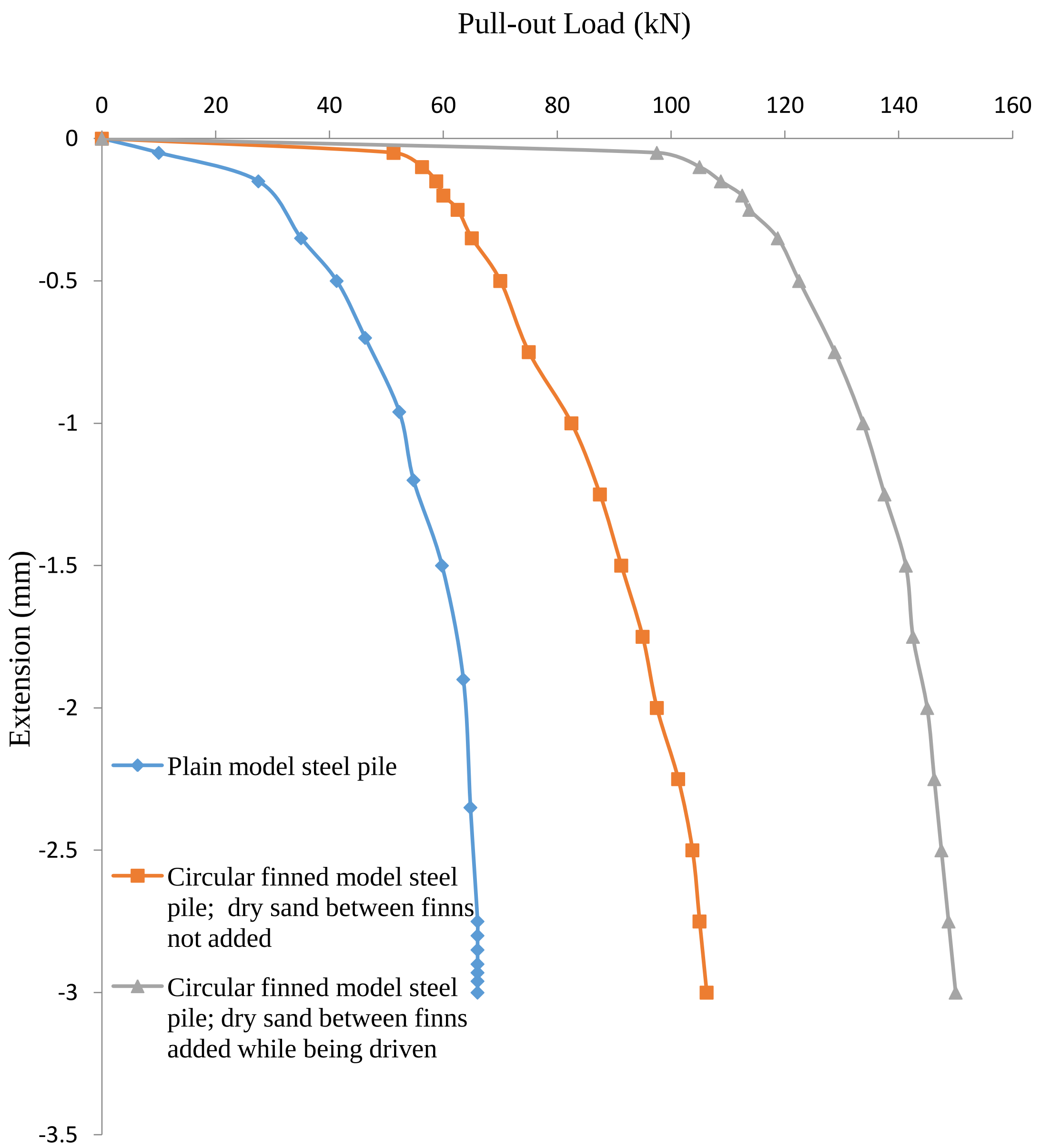
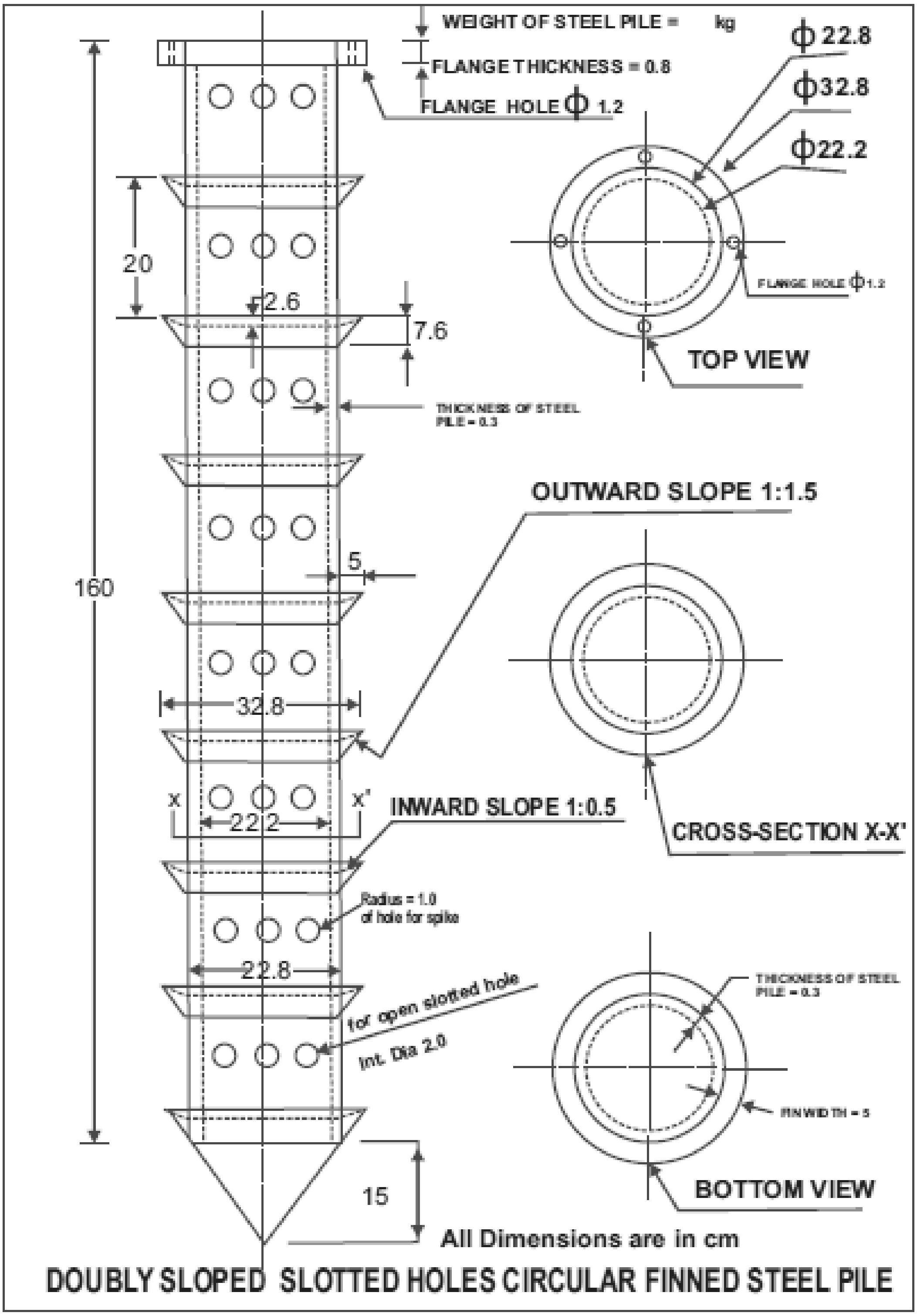


Figure 25: Graph showing comparison between side resistances for Pull-out load vs. Extension for doubly sloped circular finned (faced vertically upwards) model steel pile with circular fins. In its second test, dry sand was added and manually compacted in between the fins while the steel pile was being driven inside the dry sand.



Drawing 22. Doubly sloped slotted holes circular finned (faced vertically upwards) steel pile with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals; Weight of steel pile=46.1 kg. In its third test, dry sand was added and manually compacted in between the fins while the steel pile was being driven inside the dry sand.

Table 25. Pull-out load vs. Extension for Doubly sloped slotted holes circular finned (faced vertically upwards) model steel pile with circular fins. In its third test, dry sand was added and manually compacted in between the fins while the steel pile was being driven inside the dry sand.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	92.50	92.50
2	0.10	0.10	0.10	0.05	-0.10	5.00	97.50
3	0.16	0.14	0.15	0.05	-0.15	5.00	102.50
4	0.21	0.19	0.20	0.05	-0.20	2.50	105.00
5	0.26	0.24	0.25	0.05	-0.25	2.50	107.50
6	0.36	0.34	0.35	0.10	-0.35	5.00	112.50
7	0.51	0.49	0.50	0.15	-0.50	6.25	118.75
8	0.76	0.74	0.75	0.25	-0.75	8.75	127.50
9	1.01	0.99	1.00	0.25	-1.00	6,25	133.75
10	1.26	1.24	1.25	0.25	-1.25	6.25	140.00
11	1.51	1.49	1.50	0.25	-1.50	3.75	143.75
12	1.76	1.74	1.75	0.25	-1.75	2.50	146.25
13	2.01	1.99	2.00	0.25	-2.00	2.50	148.75
14	2.26	2.24	2.25	0.25	-2.25	2.50	151.25
15	2.51	2.49	2.50	0.25	-2.50	1.25	152.50
16	2.76	2.74	2.75	0.25	-2.75	1.25	153.75
18	Cont. increase	Cont. increase	-	-	Continuous increase	zero	153.75

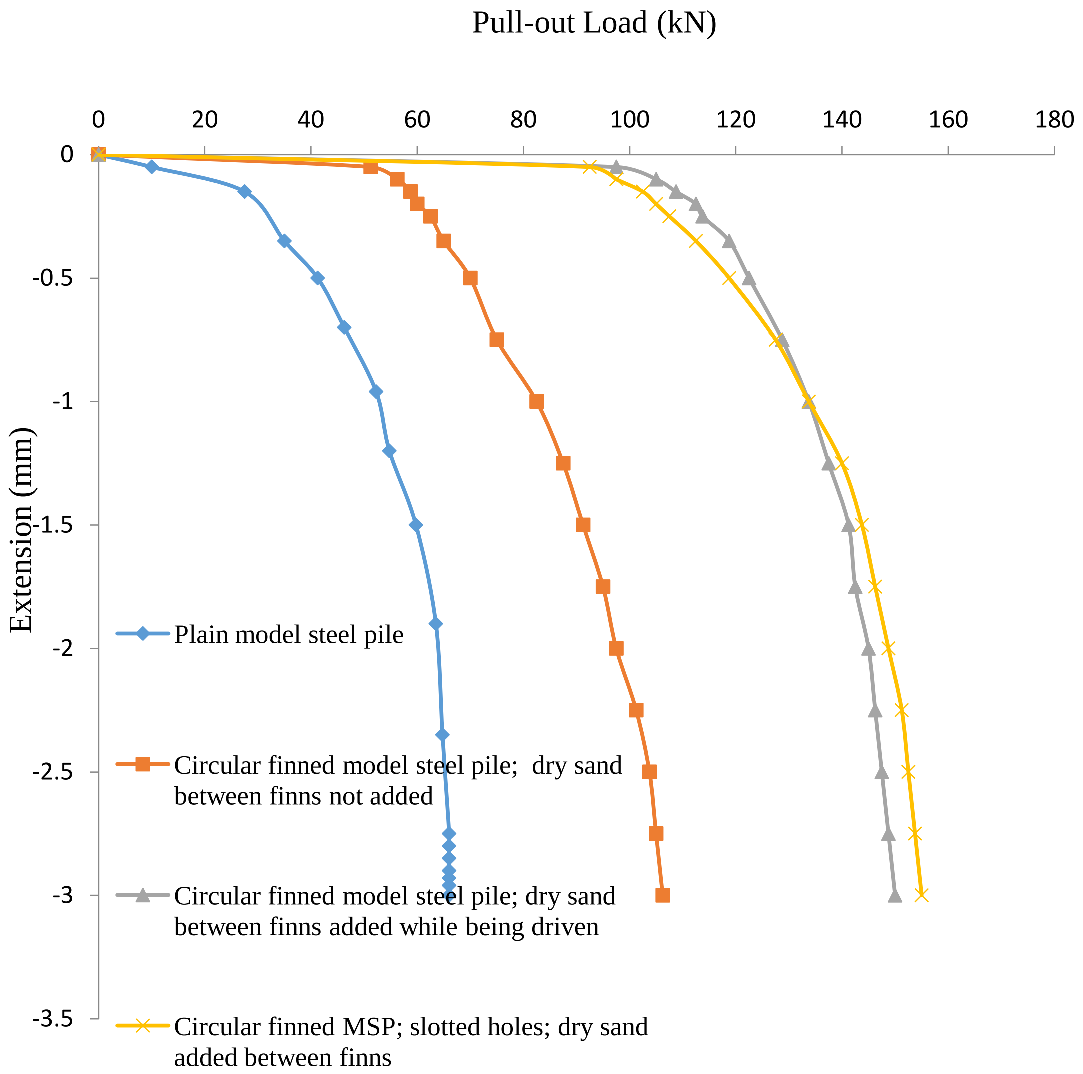
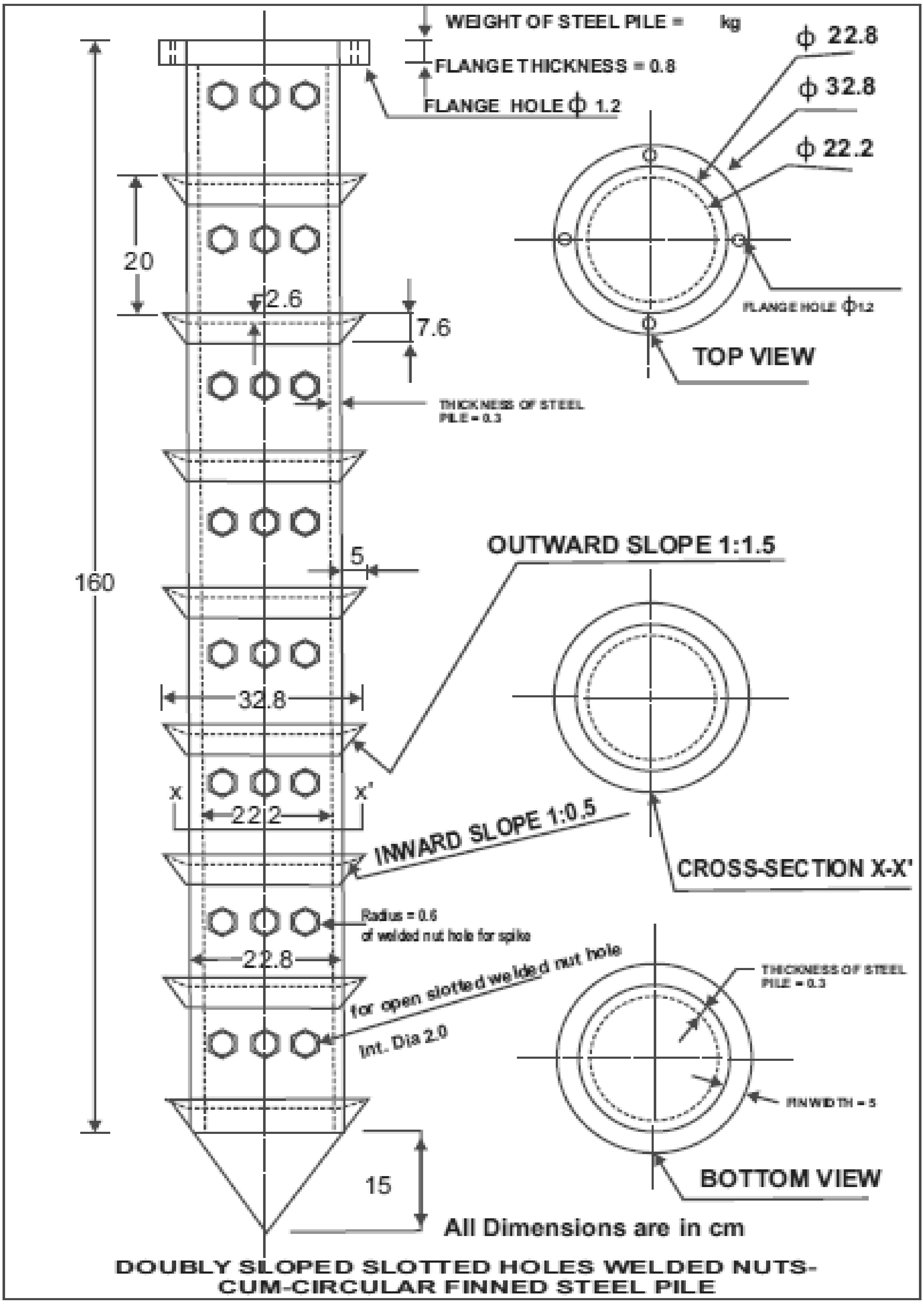


Figure 26: Graph showing comparison between side resistances for Pull-out load vs. Extension for doubly sloped circular finned (faced vertically upwards) model steel pile with circular fins. In its third test, dry sand was added and manually compacted in between the fins while the steel pile was being driven inside the dry sand.



Drawing 23. Doubly sloped slotted holes welded nuts –cum-circular finned (faced vertically upwards) steel pile with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals; Weight of steel pile=46.7 kg. In fourth test dry sand was added and manually compacted in between the fins while the steel pile is being driven inside the dry sand

Table 26. Pull-out load vs. Extension for Doubly sloped slotted holes welded nuts-cum- circular finned (faced vertically upwards) model steel pile with circular fins.In its fourth test, dry sand was added and manually compacted in between the fins while the steel pile was being driven inside the dry sand.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	93.75	93.75
2	0.10	0.10	0.10	0.05	-0.10	5.00	98.75
3	0.16	0.14	0.15	0.05	-0.15	5.00	103.75
4	0.21	0.19	0.20	0.05	-0.20	2.50	106.25
5	0.26	0.24	0.25	0.05	-0.25	3.75	110.00
6	0.36	0.34	0.35	0.10	-0.35	5.00	115.00
7	0.51	0.49	0.50	0.15	-0.50	6.25	121.25
8	0.76	0.74	0.75	0.25	-0.75	8.75	130.00
9	1.01	0.99	1.00	0.25	-1.00	6.25	136.25
10	1.26	1.24	1.25	0.25	-1.25	6.25	142.50
11	1.51	1.49	1.50	0.25	-1.50	5.00	147.50
12	1.76	1.74	1.75	0.25	-1.75	2.50	150.00
13	2.01	1.99	2.00	0.25	-2.00	2.50	152.50
14	2.26	2.24	2.25	0.25	-2.25	2.50	155.00
15	2.51	2.49	2.50	0.25	-2.50	2.50	157.50
16	2.76	2.74	2.75	0.25	-2.75	1.25	158.75
17	3.01	2.99	3.00	0.25	-3.00	1.25	160.00
18	Cont. increase	Cont. increase	-	-	Continuous increase	zero	160.00

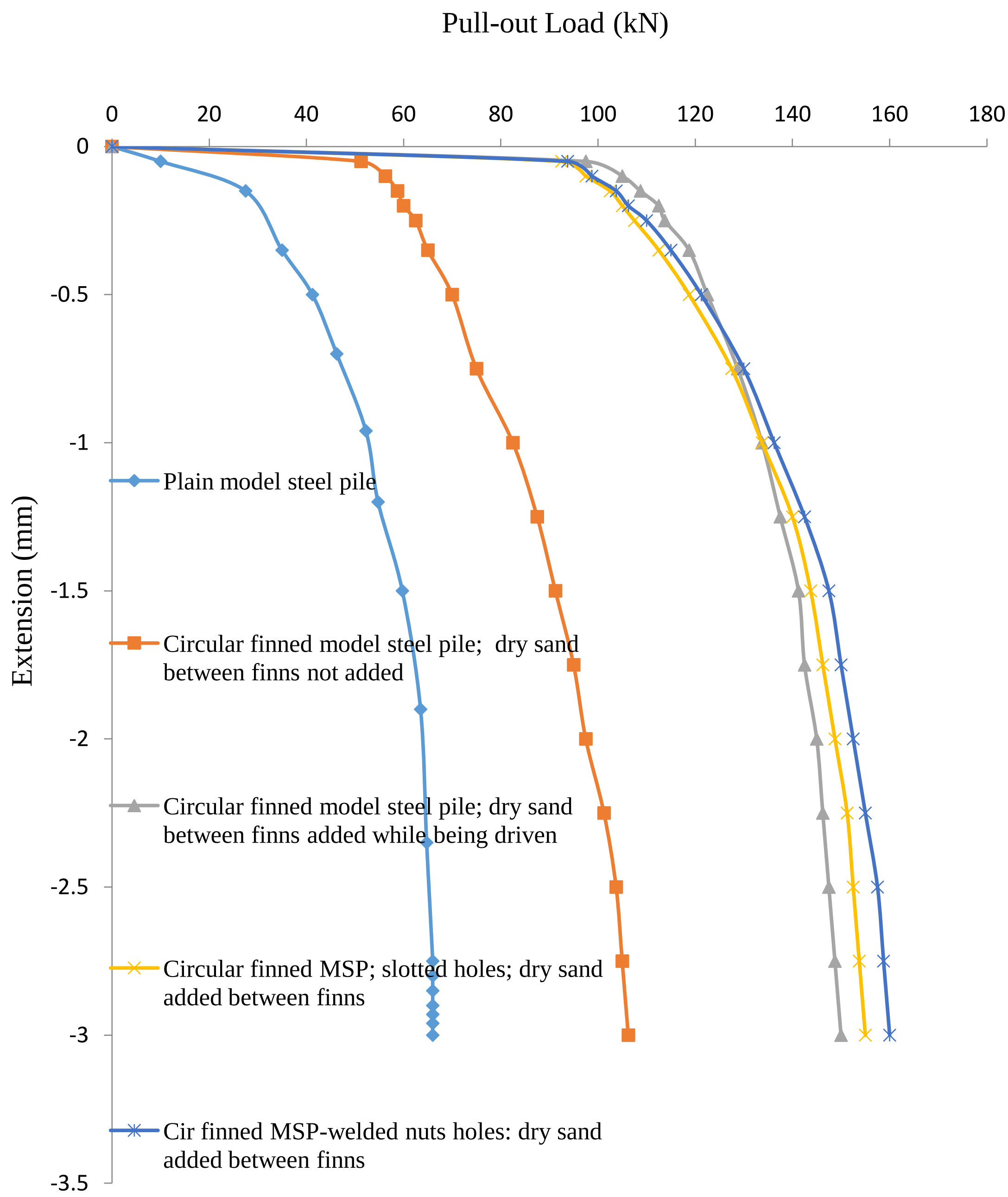
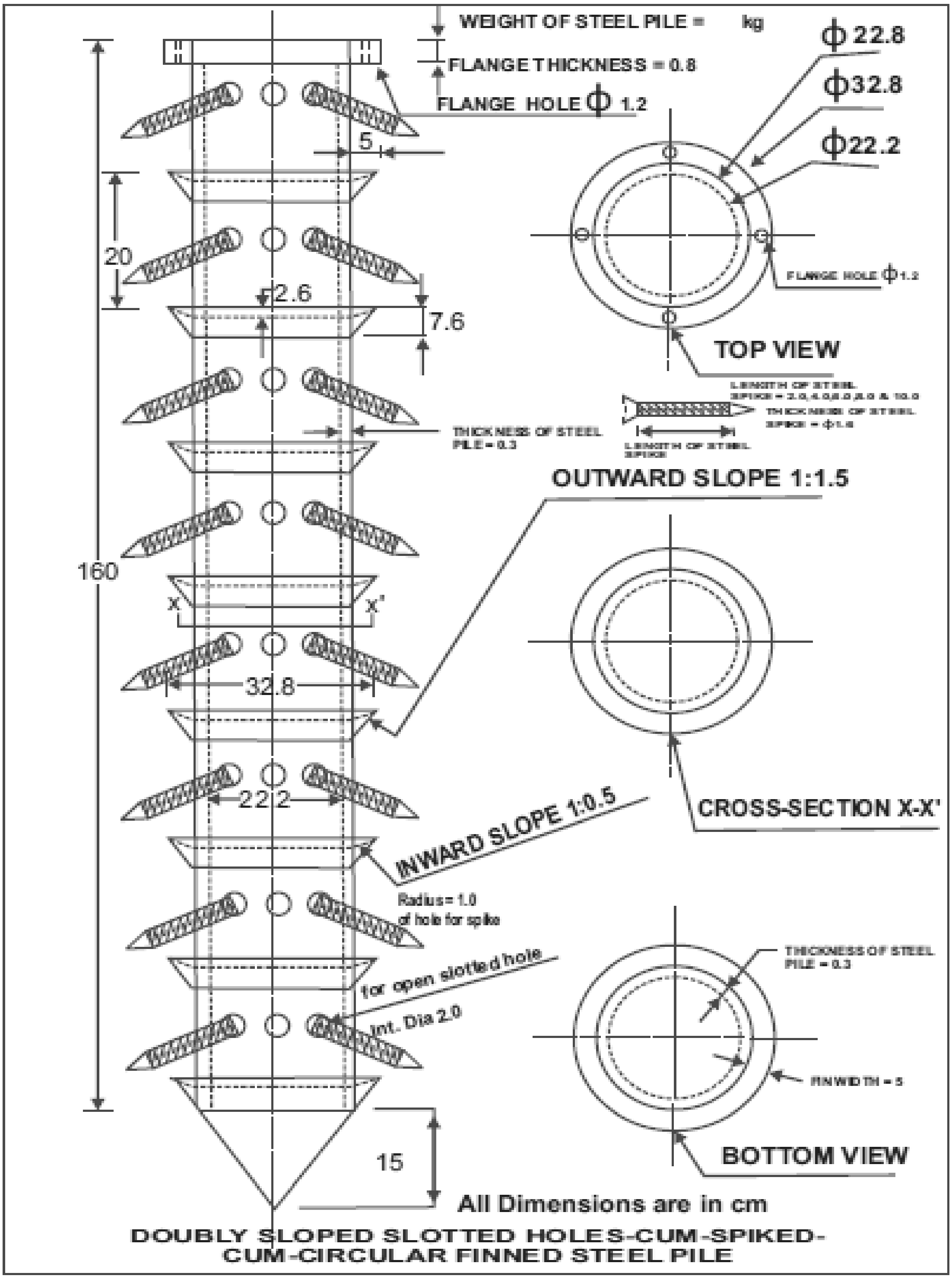


Figure 27: Graph showing comparison between side resistances for Pull-out load vs. Extension for Doubly sloped slotted holes circular finned (faced vertically upwards) model steel pile with circular fins. In its fourth test, dry sand was added and manually compacted in between the fins while the steel pile was being driven inside the dry sand.



Drawing 24. Doubly sloped slotted holes–cum-spiked-cum-circular finned (faced vertically upwards) model steel pile-90º- 06/10 with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals; Weight of steel pile=53.7 kg. In its fifth test, dry sand was added and manually compacted in between the fins while the steel pile was being driven inside the dry sand.

Table 27. Pull-out load vs. Extension for doubly sloped slotted holes–cum-spiked-cum-circular finned (faced vertically upwards) model steel pile-90º-06/10 with circular fins. In its fifth test, dry sand was added and manually compacted in between the fins while the steel pile was being driven inside the dry sand.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	93.50	93.50
2	0.10	0.10	0.10	0.05	-0.10	5.00	98.50
3	0.16	0.14	0.15	0.05	-0.15	5.00	103.50
4	0.21	0.19	0.20	0.05	-0.20	2.50	106.00
5	0.26	0.24	0.25	0.05	-0.25	2.50	108.50
6	0.36	0.34	0.35	0.10	-0.35	5.00	113.50
7	0.51	0.49	0.50	0.15	-0.50	6.25	119.75
8	0.76	0.74	0.75	0.25	-0.75	7.50	126.25
9	1.01	0.99	1.00	0.25	-1.00	6,25	132.50
10	1.26	1.24	1.25	0.25	-1.25	6.25	138.75
11	1.51	1.49	1.50	0.25	-1.50	3.75	142.50
12	1.76	1.74	1.75	0.25	-1.75	3.75	146.25
13	2.01	1.99	2.00	0.25	-2.00	2.50	148.75
14	2.26	2.24	2.25	0.25	-2.25	2.50	151.25
15	2.51	2.49	2.50	0.25	-2.50	1.25	152.50
16	2.76	2.74	2.75	0.25	-2.75	1.25	153.75
17	3.01	2.99	3.00	0.25	-3.00	1.25	155.00
18	Cont. increase	Cont. increase	-	-	Continuous increase	zero	155.00

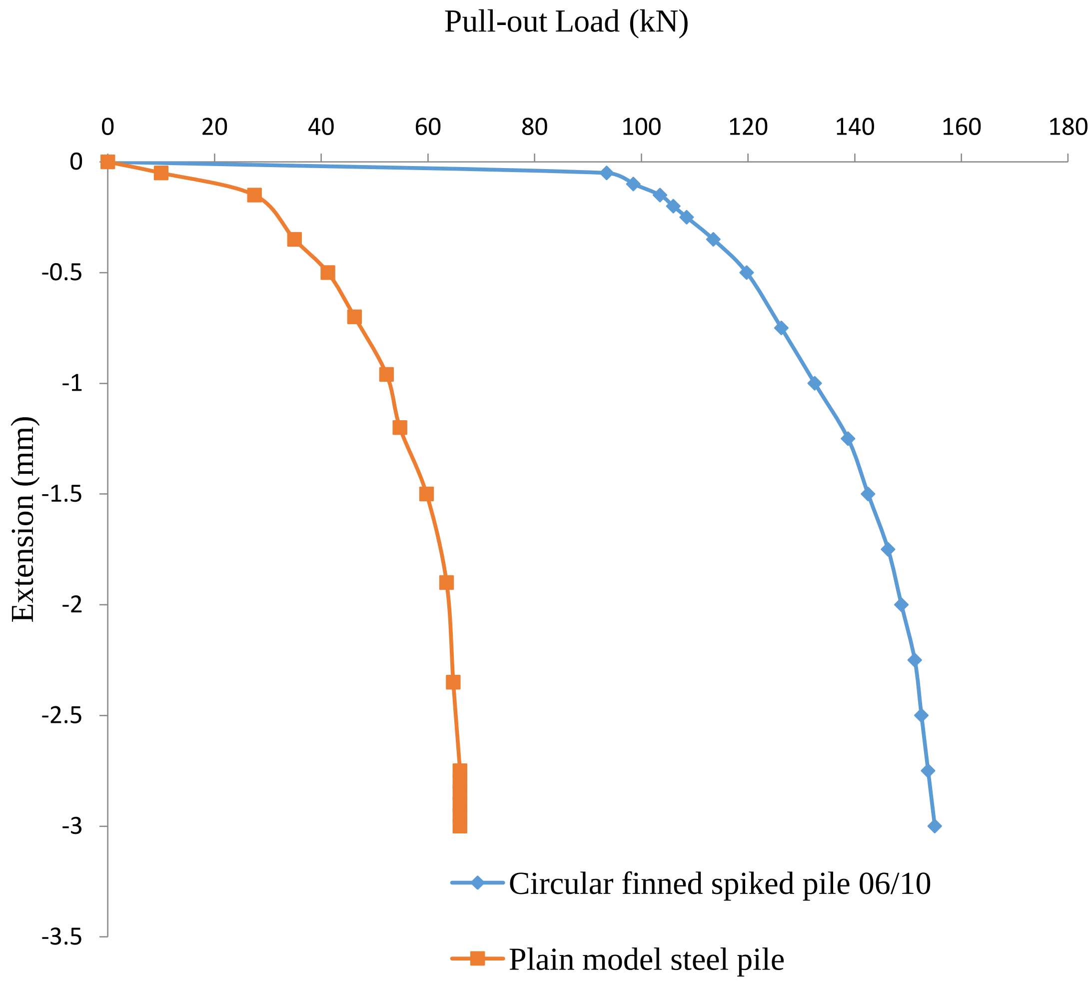
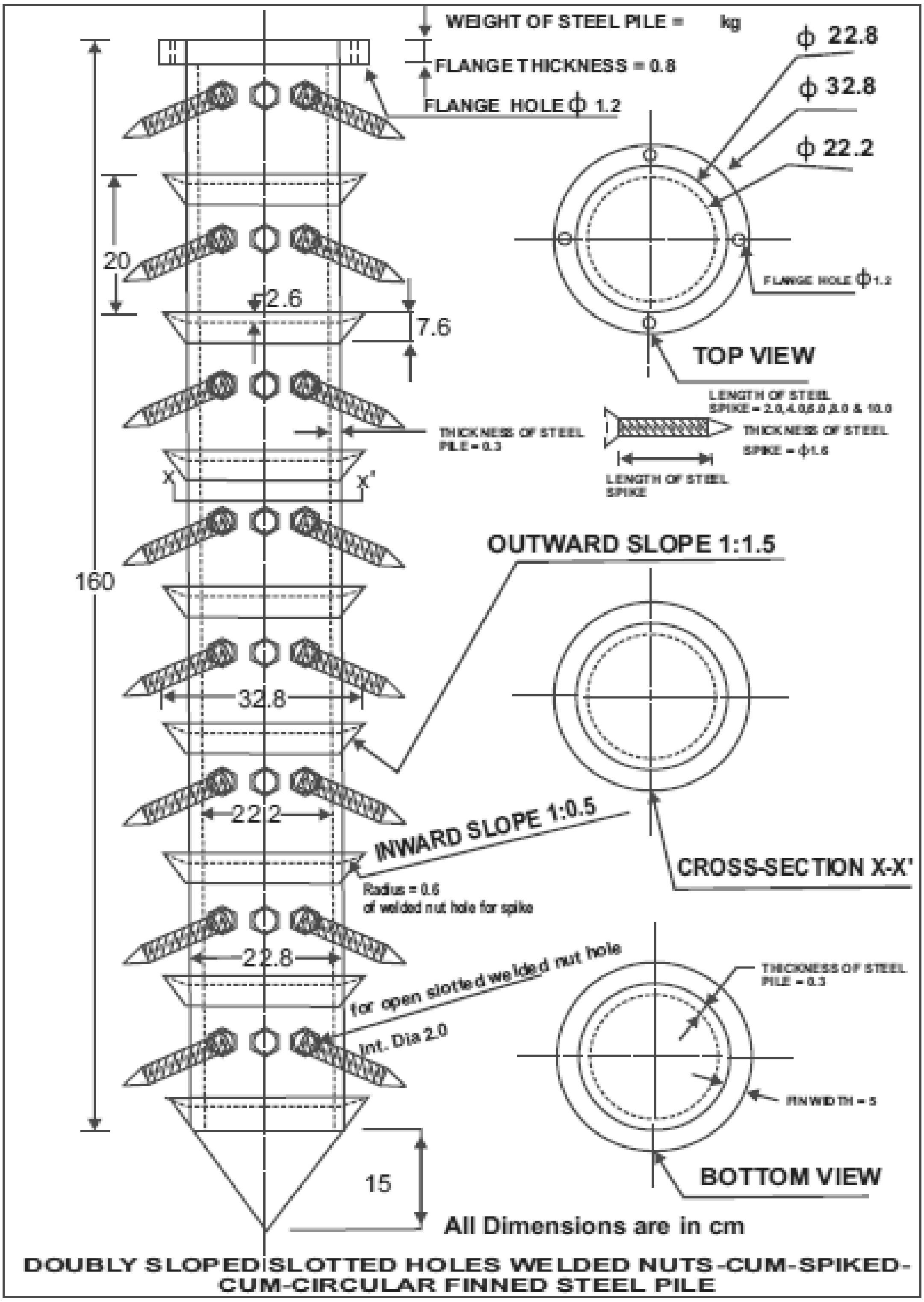


Figure 28: Graph showing comparison between side resistances for doubly sloped slotted holes–cum-spiked-cum-circular finned (faced vertically upwards) model steel pile-90º- 06/10 with circular fins. In its fifth test, dry sand was added and manually compacted in between the fins while the steel pile was being driven inside the dry sand.



Drawing 25. Doubly sloped slotted holes –cum-spiked-cum-circular finned (faced vertically upwards) model steel pile-90º - 08/10 with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals; Weight of steel pile=55.2 kg. In its sixth test, dry sand was added and manually compacted in between the fins while the steel pile was being driven inside the dry sand.

Table 28. Pull-out load vs. Extension for doubly sloped slotted holes–cum-spiked-cum-circular finned (faced vertically upwards) model steel pile-90º- 08/10 with circular fins. In its sixth test, dry sand was added and manually compacted in between the fins while the steel pile was being driven inside the dry sand.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	97.50	97.50
2	0.10	0.10	0.10	0.05	-0.10	5.00	102.50
3	0.16	0.14	0.15	0.05	-0.15	6.25	108.75
4	0.21	0.19	0.20	0.05	-0.20	2.50	111.25
5	0.26	0.24	0.25	0.05	-0.25	3.75	115.00
6	0.36	0.34	0.35	0.10	-0.35	5.00	120.00
7	0.51	0.49	0.50	0.15	-0.50	7.50	127.50
8	0.76	0.74	0.75	0.25	-0.75	8.75	136.25
9	1.01	0.99	1.00	0.25	-1.00	6,25	142.50
10	1.26	1.24	1.25	0.25	-1.25	7.50	150.00
11	1.51	1.49	1.50	0.25	-1.50	3.75	153.75
12	1.76	1.74	1.75	0.25	-1.75	3.75	157.50
13	2.01	1.99	2.00	0.25	-2.00	2.50	160.00
14	2.26	2.24	2.25	0.25	-2.25	3.75	163.75
15	2.51	2.49	2.50	0.25	-2.50	1.25	165.00
16	2.76	2.74	2.75	0.25	-2.75	1.25	166.25
17	3.01	2.99	3.00	0.25	-3.00	1.25	167.50
18	Cont. increase	Cont. increase	-	-	Continuous increase	zero	167.50

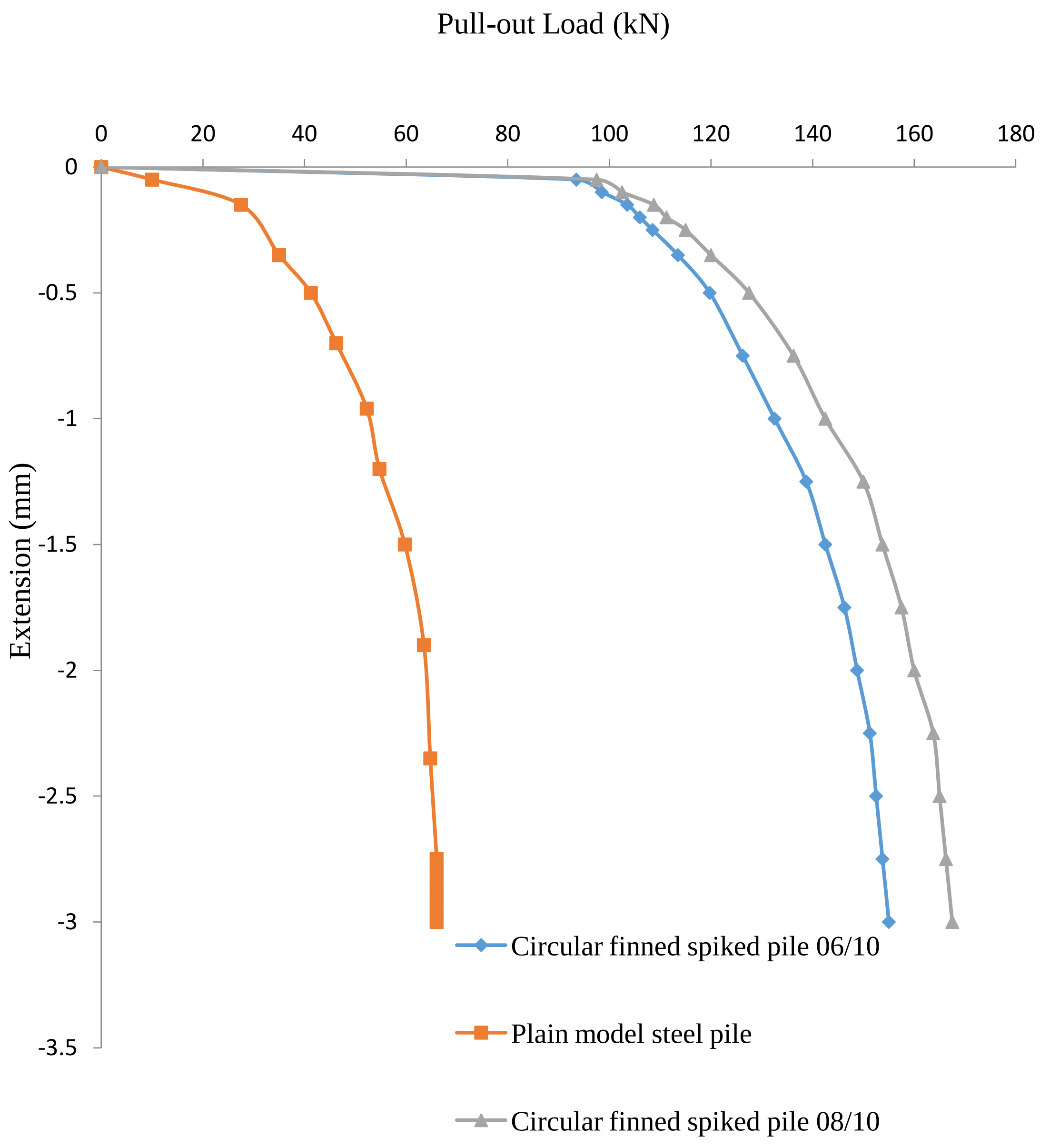
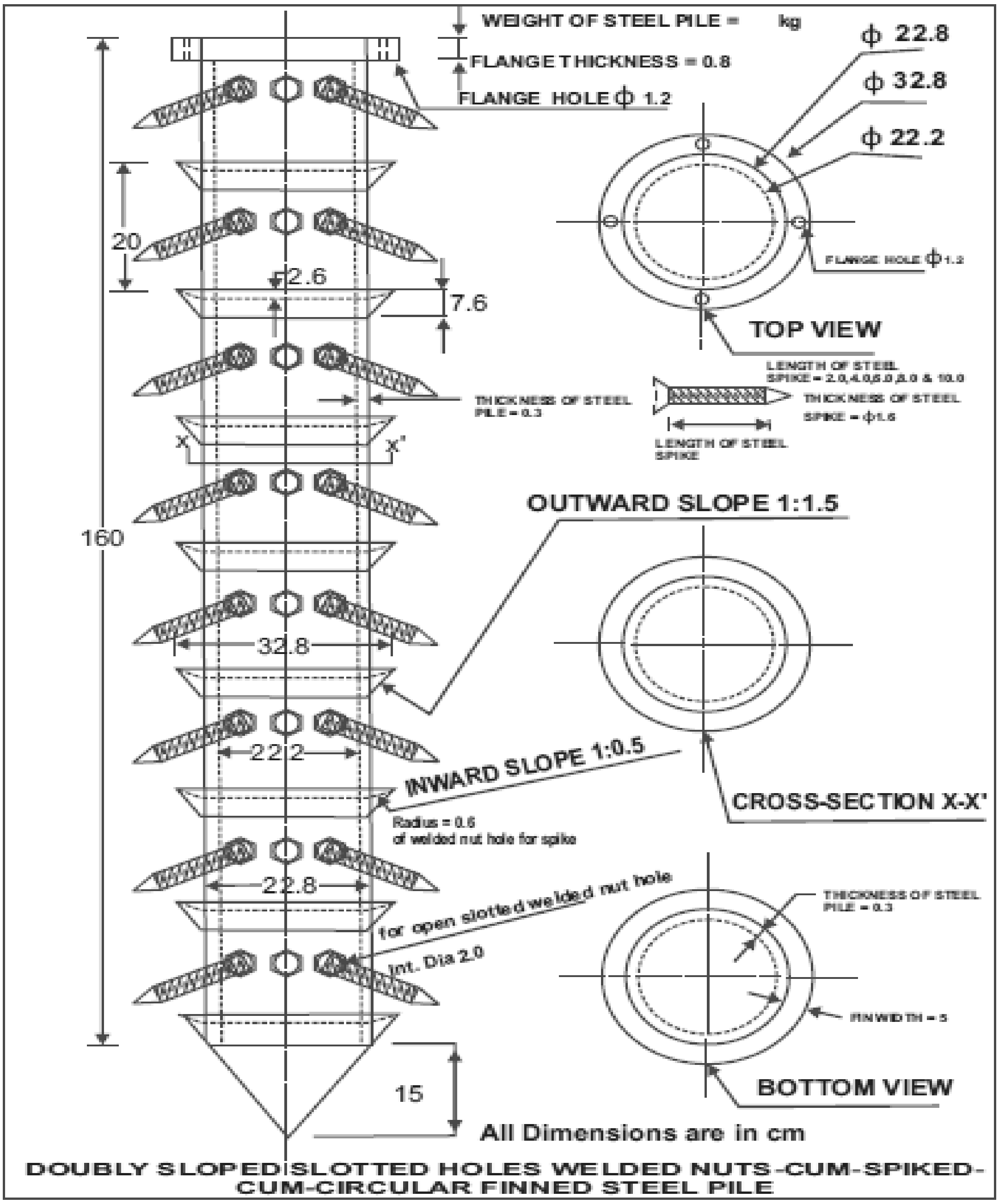


Figure 29: Graph showing comparison between side resistances for doubly sloped slotted holes–cum-spiked-cum-circular finned (faced vertically upwards) model steel pile-90º- 08/10 and 06/10 with circular fins. In its sixth test, dry sand was added and manually compacted in between the fins while the steel pile was being driven inside the dry sand.



Drawing 26. Doubly sloped slotted holes welded nuts –cum-spiked-cum-circular finned (faced vertically upwards) model steel pile-90º-10/10 with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals; Weight of steel pile = 56.7 kg. In its seventh test, dry sand was added and manually compacted in between the fins while the steel pile was being driven inside the dry sand.

Table 29. Pull-out load vs. Extension for doubly sloped slotted holes–cum-spiked-cum-circular finned (faced vertically upwards) model steel pile-90º- 10/10 with circular fins. In its seventh test, dry sand was added and manually compacted in between the fins while the steel pile was being driven inside the dry sand.

S. No	Extension (mm)				Cumulative Extension (mm) – ve sign shows opposite of settlement	Incremental Load (kN)	Cumulative Load (kN)
	Dial Gauge No.1 Reading	Dial Gauge No.2 Reading	Mean Reading of the Two Dial Gauges	Present Mean Reading - Previous Mean Reading			
1	0.05	0.05	0.05	0.05	-0.05	102.50	102.50
2	0.10	0.10	0.10	0.05	-0.10	5.00	107.50
3	0.16	0.14	0.15	0.05	-0.15	6.25	113.75
4	0.21	0.19	0.20	0.05	-0.20	3.75	117.50
5	0.26	0.24	0.25	0.05	-0.25	3.75	121.25
6	0.36	0.34	0.35	0.10	-0.35	5.00	126.25
7	0.51	0.49	0.50	0.15	-0.50	7.50	133.75
8	0.76	0.74	0.75	0.25	-0.75	8.75	142.50
9	1.01	0.99	1.00	0.25	-1.00	7.50	150.00
10	1.26	1.24	1.25	0.25	-1.25	7.50	157.50
11	1.51	1.49	1.50	0.25	-1.50	5.00	162.50
12	1.76	1.74	1.75	0.25	-1.75	3.75	166.25
13	2.01	1.99	2.00	0.25	-2.00	3.75	170.00
14	2.26	2.24	2.25	0.25	-2.25	3.75	173.75
15	2.51	2.49	2.50	0.25	-2.50	1.25	175.00
16	2.76	2.74	2.75	0.25	-2.75	1.25	176.25
17	3.01	2.99	3.00	0.25	-3.00	1.25	176.50
18	Cont. increase	Cont. increase	-	-	Continuous increase	zero	176.50

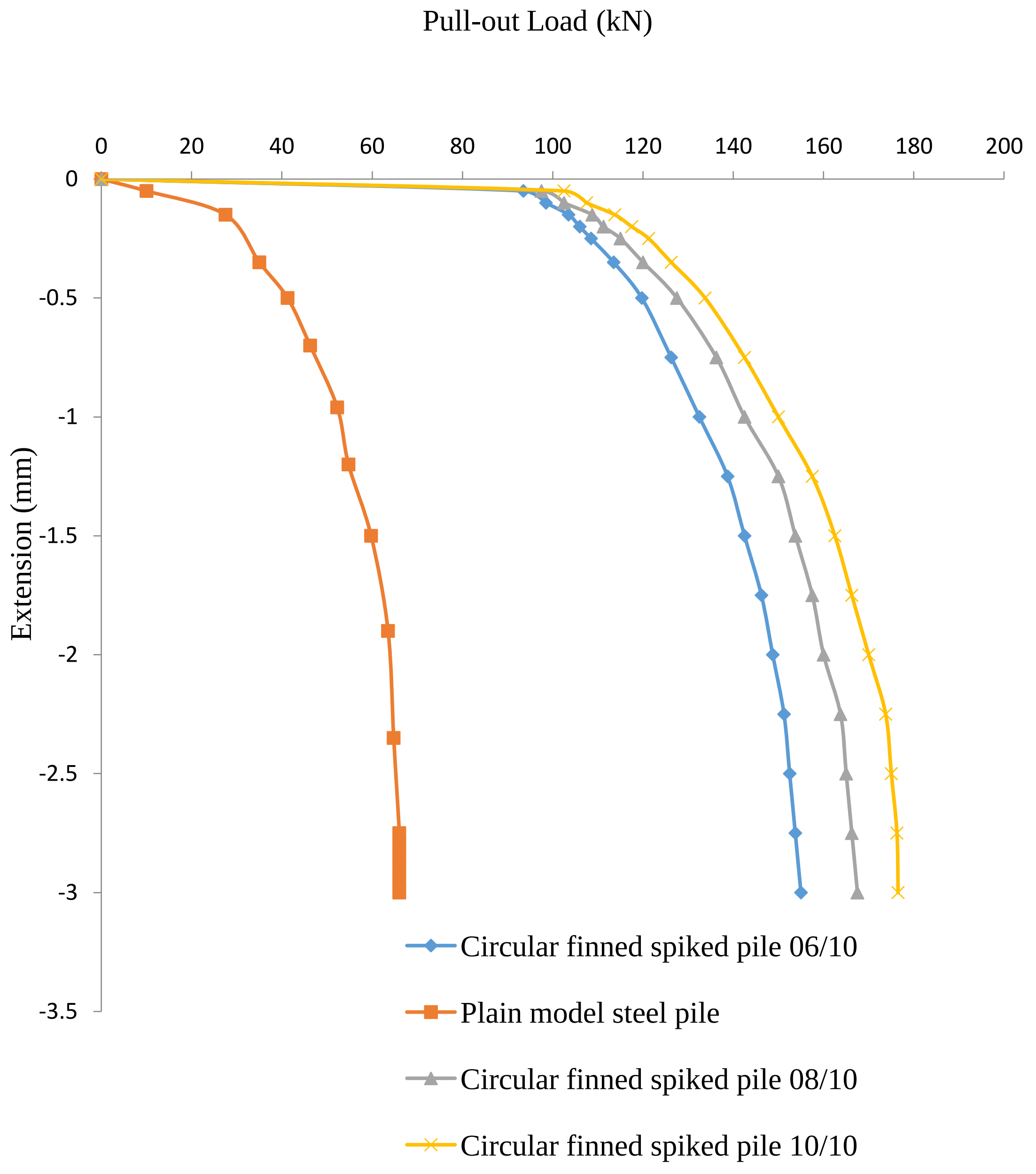


Figure 30: Graph showing comparison between side resistances for doubly sloped slotted holes–cum-spiked-cum-circular finned (faced vertically upwards) model steel pile-90º- 10/10, 08/10 and 06/10 with circular fins. In its seventh test, dry sand was added and manually compacted in between the fins while the steel pile was being driven inside the dry sand.

Side resistances of various specially featured steel piles have been compared with each other by a factor ξ known as improvement factor which is equal to ratio of side resistance of specially featured model steel pile to that of side resistance of plain model steel pile (MSP).

Drawing 1	Plain model steel pile (MSP).	ξ = 1.000
Drawing 2	Slotted holes model steel pile.	ξ = 1.167
Drawing 3	Welded nut slotted holes model steel pile.	ξ = 1.136
Drawing 4	Spike of length 2.0 cm and dia. 10 mm through slotted holes at 90º.	ξ = 1.250
Drawing 5	Spike of length 4.0 cm and dia. 10 mm through slotted holes at 90º.	ξ = 1.477
Drawing 6	Spike of length 6.0 cm and dia. 10 mm through slotted holes at 90º.	ξ = 1.686
Drawing 7	Spike of length 8.0 cm and dia. 10 mm through slotted holes at 90º.	ξ = 1.837
Drawing 8	Spike of length 10.0 cm and dia. 10 mm through slotted holes at 90º.	ξ = 1.951
Drawing 9	Spike of length 2.0 cm and dia. 8 mm through slotted holes at 90º.	ξ = 1.174
Drawing 10	Spike of length 4.0 cm and dia. 8 mm through slotted holes at 90º.	ξ = 1.402
Drawing 11	Spike of length 6.0 cm and dia. 8 mm through slotted holes at 90º.	ξ = 1.591

Drawing 12	Spike of length 8.0 cm and dia. 8 mm through slotted holes at 90º.	ξ =	1.743
.Drawing 13	Spike of length 10.0 cm and dia. 8 mm through slotted holes at 90º.	ξ =	1.837
Drawing 14	Slotted holes-cum-Inclined spikes of length 10.0 cm and dia. 10 mm at 30º inclination at a point w.r.t. positive direction of vertical plumb line.	ξ =	1.553
Drawing 15	Slotted holes-cum-Inclined spikes of length 10.0 cm and dia. 10 mm at 60º inclination at a point w.r.t. positive direction of vertical plumb line.	ξ =	1.989
Drawing 16	Slotted holes-cum-Inclined spikes of length 10.0 cm and dia. 10 mm at 90º inclination at a point w.r.t. positive direction of vertical plumb line.	ξ =	1.951
Drawing 17	Slotted holes-cum-Inclined spikes of length 10.0 cm and dia. 10 mm at 120º inclination at a point w.r.t. positive direction of vertical plumb line.	ξ =	1.705
Drawing 18	Slotted holes-cum-Inclined spikes of ξlength 10.0 cm and dia. 10 mm at 150º inclination at a point w.r.t. positive direction of vertical plumb line.	ξ =	1.534
Drawing 19	Spike of length 10.0 cm and dia. 10 cm through slotted hole inclined at exactly 90º (orthogonal direction).	ξ =	1.989
Drawing 20	Doubly sloped circular finned (faced vertically upwards) model steel pile with circular fins 5.0 cm widewith top fin surface at inward slope of 1:1/2 and bottom fin surface at upward slope of 1:1.5provided at 20.0 cm intervals. Dry sand is not added	ξ =	1.609

manually in between the fins while the steel pile is being driven inside the dry sand.

Drawing 21	Doubly sloped circular finned (faced vertically upwards) model steel pile with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at upward slope of 1:1.5 provided at 20.0 cm intervals. Dry sand is added and manually compacted in between the fins while the steel pile is being driven inside the dry sand.	$\xi =$ 2.273
Drawing 22	Doubly sloped slotted holes circular finned (faced vertically upwards) steel pile with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals. Dry sand is added and manually compacted in between the fins while the steel pile is being driven inside the dry sand.	$\xi =$ 2.329
Drawing 23	Doubly sloped slotted holes welded nuts–cum-circular finned (faced vertically upwards) steel pile with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals	$\xi =$ 2.424
Drawing 24	Doubly sloped slotted holes–cum-spiked-cum-circular finned (faced vertically upwards) model steel pile-90º - 06/10 with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals	$\xi =$ 2.349
Drawing 25	Doubly sloped slotted holes–cum-spiked-cum-circular finned (faced vertically	$\xi =$ 2.538

	upwards) model steel pile-90º - 08/10 with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm interval	
Drawing 26	Doubly sloped slotted holes welded nuts-cum-spiked-cum-circular finned (faced vertically upwards) model steel pile-90º - 10/10 with circular fins 5.0 cm wide with top fin surface at inward slope of 1:1/2 and bottom fin surface at 1:1.5 provided at 20.0 cm intervals.	$\xi =$ 2.674

These improvement factors, ξ – zeta corresponding to their respective model steel piles have been discussed thoroughly under the chapter, "Results and Discussions".

A model steel pile having slotted holes had higher side resistance when driven fully than with that of a corresponding model steel pile without slotted holes.

After being driven fully into the ground, the side resistance capacity of the model steel pile having slotted holes was 16.67 % higher than the model steel pile having no holes.

Then, the effect of spikes was checked. First of all, plain spikes were put through the slotted holes from inside of the driven pile (the details are shown in the photographs in the chapter III on, “Experimental Programme”). As the exact orthogonality of the plain spikes passing through the slotted holes was difficult to maintain, due to little side-way slip-cum-play between slotted hole and spike. Later on, to maintain exact inclination of spikes, high tensile nuts were welded behind the slotted holes, inside the two halves of model steel pile, at desired degree of angle of inclination of spikes w.r.t. vertical plumb line at a point of slotted hole of a model steel pile. Welded nuts were also used in some of tests for doubly sloped-cum-spiked-cum-finned model steel pile. Somehow, side-resistances of model steel piles with plain spikes were taken. The side-resistances of respective model steel piles having plain spikes were compared with model steel piles with and without slotted holes. The side resistances w.r.t. plain model steel pile were found to be increased by 25%, 47.73%, 68.56%, 83.71% and 95.08% in correspondence with increase of 10 mm diameter spikes length by 2 cm, 4 cm, 6 cm, 8 cm and 10 cm respectively. When, the dia. of spikes was changed from 10 mm to 8 mm, the respective increases w.r.t. plain model steel pile were found to be 17.42%, 40.15%, 59.09%, 74.24% and 83.71%. The differences in increased side resistances corresponding to 10 mm diameter and 8 mm diameter spikes and that, too, w.r.t. 2 cm, 4 cm. 6 cm, 8 cm and 10 cm were found to be 7.58%, 7.58%, 9.47%, 9.47% and 11.37% respectively. The main inference from the results was that for corresponding lesser lengths of spikes w.r.t. 10 mm diameter and 8 mm diameter, the reduction in percentage of side resistances were also lesser for lesser lengths of spikes and larger for larger lengths of spikes. Therefore, it is concluded that this is due to more stressed state of soil mass (dry Yamuna Sand) near the periphery of model steel pile. Normally, it is due to jacking of model steel pile while being jacked into the soil mass as well as more compact state of soil-structure interaction nearer the periphery of model steel pile. This result gives credence to the prevalent thought that jacked steel piles have more side resistance than that of hammer driven steel piles and also the compactness of soil mass reduces in proportion to the increase of radius from the centre of steel pile. This reduction in compactness leads to reduction of side resistance coming from end portion spike lengths. Hence, the question arises, whether is it wise enough to go for larger length of spikes? The answer, naturally, comes is yes, because it is definitely increasing the side resistance and becoming a major component of load holding capacity of a particular pile. But, another point of view would be why we should spend more for larger length of spikes while side resistance for per unit run of spike length reduces as we move away from the centre of pile. Here, it requires a decision?

In general, a balanced limit approach could be adopted from spacing of spikes on the same pile and between the spike's length from parent pile and spikes from neighbourhood of piles. It is suggested that further research is required for inter combination of group effect of spikes in the group action of piles.

The pattern of spikes in its group action of spikes could play a major role in sum up of side resistance for a group action of piles because of fear of some overlapping portions of pressure bulbs being formed in the vicinity of concentrated zones of mush-rooming of spikes.

Of course, these side-resistances of model steel piles with plain spikes were compared with side-resistances of model steel piles with threaded bolts in the form of spikes having orthogonality as well as inclination, upwards and downwards at various real angle of inclinations i.e. β^o +/- θ^o, with the upward + ve direction of plumb line.

The high tensile steel bolts were put inside the welded nuts, taking care that in first experiment, the bolts didn't spike out of the lateral surface area.

Many more experiments were conducted with, almost orthogonal not exactly orthogonal, spikes coming out of lateral surface area of the pile at 2 cm, 4 cm, 6 cm, 8 cm and 10 cm, as detailed in the chapter III of, "Experimental Programme". The side-resistances of respective model steel piles were compared with one another in the form of zeta factor, ξ an improvement factor.

From the results, it came out that higher the length of spikes from the outer surface of model steel pile, higher its side-resistance will be in totality, but, incremental increase in length of spikes leads to reduction in rate of gain in side resistance as we move away from the centre of model steel pile.

As the side-resistances of model steel piles having threaded surface of spikes were 3.78% greater than the side-resistance of model steel piles having plain surface of spikes.

From the results, it came out that, as the inclination factor of spike β^o (subject to a maximum of $\beta^o = 180^o +/- \theta^o$) increases from 0º to 60º, the side resistance of the spikes increases and similarly, an increase from60º onwards up to180º, decreases the side resistance and rate of increase is more. The main inference from the results is coming that inclined length of full spike at 30º is half of that of equivalent orthogonal effect of full length spike had it been at an angle of inclination of 90º. It can even be calculated by simple trigonometrical formulae of right angled triangle. Similarly, inclined length of full spike at 60º is 0.866 times that of equivalent orthogonal effect of full length spike had it been at an angle of inclination of 90º. Therefore, in spite of 13.4% lesser length of equivalent orthogonal effect of full length of spike, the side resistance is still higher by 3% than that of equivalent orthogonal effect of full length at 90º. It was due to wedging action of lump sum of soil mass resting on inclined spikes at bottom. Additionally due to presence of some finer particles in the dry sand giving it a little cohesion effect and on being pull-out of pile through soil-mass giving it a compact state of dry sand containing little finer particles due to wedging action of soil-mass while being pull –out of pile. Similarly, when the inclination of spikes moves from 90º to 120º the rate of decrease of side-resistance (i.e. 24.62 %) happens to be much more than the rate of decrease from 60º to 90º (i.e. 3%). It was due to opposite of wedging action. Here, the soil mass on being pull-out of pile tends to loosen out due to gravity of soil mass from the spikes. Similarly, the rate of decrease is again 17.05% when the angle of inclination of spikes moves from 120º to 150º.Here again the inclined length of full spike at 150º is half of that of equivalent orthogonal effect of full length spike had it been at an angle of inclination of 90º. So, reduction in spike length along with gravity leads to further loosening of dry soil mass (dry Yamuna sand containing little finer particles).

Similarly, to avoid the effect of applied torque due to surrounding soil mass on the spikes, to increase lateral side resistance due to fanning out of circular fins and giving spike holder effect at the bottom length of spikes, doubly sloped finned pile (Specifications of doubly sloped model steel finned pile are detailed in chapter III of, "Experimental Programme") was considered. The drawing of doubly sloped model steel finned pile is mentioned in drawing number 20 to 26. Its photograph of a doubly sloped model steel finned and slotted pile, one being jacked into the dry sand is given in the sub-heading of experimental procedure in chapter III of, "Experimental Programme). It was a sure shot in the effective increase of side resistance. The bottom support was provided to fins to check torque acting on fins and effective bottom slope was provided to fins so that least resistance was provided to piles while being jacked slowly inside the dry sand soil mass. Contra slope was provided to the top surface of the circular fins only to give wedging action of lump sum soil-mass. Doubly sloped circular finned (faced vertically upwards) model steel pile (In the first test dry sand was not added and compacted in between the fins) has provided 60.98% more side resistance. In the second test (dry sand was added and compacted in between the fins when it was in the process of being jacked in) has provided 127.27% more side resistance. In its third test the above finned pile was slotted and was jacked into the soil (soil was added and compacted in between the fins). It has provided 134.85% more side resistance. In its fifth test, spikes of 10 mm dia. and 6 cm length were passed through and tested. It has provided 1.89% more side resistance than that of slotted holes. The increase is very small. Its reasons were that, earlier, the side resistance was coming through slotted holes now the spikes of length 6 cm had taken over all the slotted holes, and its projected spikes are coming out through projected fins by 1cm i.e. length of spike oozing out from hole minus projected fin width i.e. (6 cm-5 cm= 1 cm). In another test, termed as fourth test, the slotted holes are welded through welded nuts. Again on its testing it showed 7.57% more side resistance that could be because of more roughened surface of finned pile due to welded nuts. In the next sixth and seventh test, spikes in the form of threaded bolts are passed through, which correspondingly gives 153.79% and 167.42% more side resistance respectively. Now, w.r.t. table of zeta factor i.e. an improvement factor, an account of improved side resistance of various model steel piles in the special featured category under spiked (orthogonal spikes and inclined spikes), doubly sloped finned (orthogonal spikes) and doubly sloped spike-finned (orthogonal spikes) is tabulated in the chapter on, "Analysis of Results".

Following conclusions are drawn from the present work, namely,

1. A model steel pile having slotted-holes has more side-resistance than a plain surface model steel pile as per the relationship of improvement factor - ξ with the side resistance of a plain model steel pile (ξ = 1.167).

2. A model steel pile having orthogonal steel spikes has much-higher side-resistance than a modal steel pile of plain surface (ξ = 1.250 to ξ = 1.989).

3. A spiked model steel pile has higher resistance than a total slotted model steel pile (ξ = 1.167 to ξ = 1.989).

4. A doubly sloped circular finned modal steel pile has more side-resistance than a plain surface modal steel pile (ξ = 1.167 to ξ = 1. 609)

5. A slotted-holes side finned modal steel pile has still more side-resistance than a side-finned modal steel pile without holes (soil is manually compacted in between the fins when driven inside the dry sand (ξ = 1.609 to ξ = 2.329)

6. A slotted-holes side-finned-cum spiked modal steel pile has the highest side-resistance. Not only, has it had an edge over other material piles for same diameter and length of pile but an eco-friendly also because of non-use of bentonite as in the case of bored and augured concrete piles (ξ =2.674).

7. Providing slotted holes, spikes, fins and spike-cum-fins makes the pile to have much more side resistance. (ξ =2.674).

Based upon the conclusions, the pull-out capacity of a plain model steel pile with special feature is recommended as improvement factor times the pull-out capacity of a plain model steel pile i.e.

Pull-out capacity of a special featured pile = P_{sf}

Pull-out capacity of a plain MSP = P_{msp}

Improvement factor =ξ

Therefore,

$$P_{sf} = \xi \times P_{msp} \qquad (5)$$

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Student Approval Form

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Degree	Degree of Philosophy in Civil Engineering
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Guide	Prof. (Dr.) A. Trivedi
Thesis of Title	Role of Special Feature in Side Resistance of a Model Steel Pile
Year of Award	2015

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Prof. (Dr.) A. Trivedi
Signature and seal of the Guide

Place: Delhi

Date: .09. 2015

1. Proper alignment of Reaction truss should be completed before placing it in its permanent position.
2. Verticality of model steel pile, while being driven, into the dry sand should be maintained through suspended plumb line.
3. Relative density of sand should be maintained by falling height of sand method, as described in the chapter III on, “Experimental Programme” as well as under the sub-heading of, “Fill Material Characteristics”.
4. Slotted holes should be cut through the steel sheet plate before moulding it into its desired shape of model steel pile.
5. Spike holder should be sufficiently strong enough to hold on the spike in its properly aligned inclined direction.
6. Corrosion powder, if any, should be removed from the external lateral surface of the model steel pile by sand blasting roughened paper before conduct of an experiment.
7. Welding of joints of model steel piles should be done by an electric arc welding method.
8. Little grinding of rough welding should be done to smoothen surface.
9. Flange plate should be fully welded to model steel pile at its proper place.
10. Pull-out holder to model steel pile via flange cover plate should be threaded at its end.
11. Base concrete should be sufficiently thick not to allow dry sand to come in contact with ground water table.
12. Hydraulic jack should be placed on to pile cap with its centre matching with that of centre of flange cover plate.

As per tradition, piles are columnar elements in a foundation which have the function of transferring load from the superstructure through weak compressible strata or through water, onto stiffer or more compact and less compressible soils or onto rock. (Randolph, M. F. 2003). But, special featured steel pile can transfer the load onto the softer and weaker compressible strata.

Not only lesser diameter, but, also shorter lengths of special featured model steel piles would be sufficient to transmit the structural loads, thereby, economising the foundation construction cost effectively.

1. Where, the soils are susceptible to liquefaction, there these types of Mesh-filtered slotted holes steel piles or Mesh-plugged slotted holes steel piles are used for immediately consolidating the soil mass.
2. Moreover, water can constantly be pumped out all along day and night, during 24 hours, for construction purposes and dewatering the water table.
3. In earth-quake prone areas, where during the time of earth-quake, due to severe ground shaking vibrations, soil-masses underneath the building foundation, having sizable sand particles, tends to liquefy, there at that time, spiked-cum-slotted holes steel piles, whose water pumps gets on by electronic sensors of earth-quake vibrations, would not only suck out extra water from the voids of liquefiable soil mass leading to immediate development of effective stresses in the soil mass (Terzaghi, 1943), but, would also be supported by the surrounded consolidated soil mass entangled as well as interlocked among the interspersed orthogonal and inclined spikes due to wedging action being provided by spikes. Also, the interlocked surrounded stressed soil-mass by spikes will act as a reinforced earth, which in-turn would provide more side-resistance, thereby, increasing the load holding as well as pull-out capacity of the steel piles at that critical juncture of earth-quake.

26 APR 2013 123 DEL 13 4111/RO-9113 D.No. 6626 1234/D113 26/4/13

ORIGINAL

FORM I
THE PATENTS ACT 1970
(39 of 1970)
&
The Patents Rules, 2003
APPLICATION FOR GRANT OF PATENT
(See section 7,54 &135and rule 20 (1))

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3. TITLE OF THE INVENTION

Slotted Holes Mesh Filtered Steel Pile

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5. PRIORITY PARTICULARS OF THE APPLICATION (S) FILED IN CONVENTION COUNTRY

Country	Application Number	Filling Date	Name of the Applicant	Title of the Invention

6. PARTICULARS FOR FILING PATENT COOPERATION TREATY (PCT) NATIONAL PHASE APPLICATION

International application number.	International filing date as allotted by the receiving office.

7. PARTICULARS FOR FILING DIV SIONAL APPLICATION

Original (first) application number.	Date of filing of Original (first) application

8. PARTICULARS FOR FILING PATENT OF ADDITION

Main application/patent Number.	Date of filing of main application

9. DECLARATIONS:

(i) Declaration by the Inventor(s)

We, the above named inventors are the true & first inventors for this invention and declare that the applicant here in is our assignee or legal representative.

(a) Date 26th April, 2013
(b) Signature(s)
(c) Name (s) NARESH KUMAR ASHUTOSH TRIVEDI

(ii) Declaration by the applicants in the convention country

We, the applicants in the convention country declare that the applicants herein are our assignee or legal representative.

(a) Date 26th April, 2013
(b) Signature(s)
(c) Name(s) of the signatory Naresh Kumar

GOVT. OF INDIA PATENT OFFICE
D. No. 6626
26 APR 2013
BAUDHIK SAMPADA BHAWAN
NEW DELHI

(III) Declaration by the applicant(s):
We, the applicant(s) hereby declare(s) that: -

- ❑ We are in possession of the above-mentioned invention
- ❑ The complete specification relating to the invention is filed with this application.
- ❑ The invention as disclosed in the specification uses the biological material from India and the necessary permission from the competent authority shall be submitted by me/us before the grant of patent to me/us.
- ❑ There is no lawful ground of objection to the grant of the Patent to us.
- ❑ We are the assignee or legal representative of true & first inventors.
- ❑ The application or each of the applications, particulars of which are given in Para - 5 was the first application in convention country/countries in respect of our invention.
- ❑ We claim the priority from the above mentioned application(s) filed in convention country/countries and state that no application for protection in respect of the invention had been made in a convention country before that date by us or by any person from which We derive the title.
- ❑ our application in India is based on international application under Patent Cooperation Treaty (PCT) as mentioned in Para - 6.
- ❑ The application is divided out of our application particulars of which is given in Para - 7 and prays that this application may be treated as deemed to have been filed on 25/04/2013 under sec.16 of the Act.
- ❑ The said invention is an improvement in or modification of the invention particulars of which are given in Para- 8,,

10. Following are the attachments with the application:

(a) Complete specification
(b) Complete specification (in conformation with the international application)/as amended before the International Preliminary Examination Authority (IPEA), as applicable (2 copies), No. of Pages 23 No. of claims 17
(c) Drawings (in conformation with the international application)/as amended before the International Preliminary Examination Authority (IPEA), as applicable (2 copies),No. of Sheets 7
(d) Priority documents
(e) Translation of priority document/Specification/International Search Report
(f) Statement and undertaking on Form 3
(g) Power of Authority
(h) Declaration of inventorship on Form 5
(i) Sequence listing in electronic form
(j) ....
Fee Rs........................in Cash,/ Cheque / Bank Draft bearing no ....
Date .... on .... Bank.

We hereby declare that to the best of my/our knowledge, information and belief the fact and matters stated herein are correct and We request that a patent may be granted to me/us for the said invention.

Dated this Twenty sixth day of April 2013

To, The Controller of Patent
The Patent Office, at...Sector-14, Dwarka
Boudhik sampada Bhavan,
Delhi

NARESH KUMAR

ASHUTOSH TRIVEDI

3.

2524 DEL 13 891 21 PO-01/13

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D. No. 2524/D/13 27/08/13

FORM I THE PATENTS ACT 1970 (39 of 1970) & The Patents Rules, 2003 APPLICATION FOR GRANT OF PATENT (See section 7,54 &135and rule 20 (1))	(FOR OFFICE USE ONLY) ApplicationNo: Filing Date: Amount of Fee Paid: CBR No: Signature:

Govt. of India, Patent Office, New Delhi Received Rs. 3000/- in Cash CHEQUE / DD ON 27 AUG 2013 Vide Entry No. 8836 in the Register of Valuables Cashier DDO

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3. TITLE OF THE INVENTION	**Slotted Holes Meshed Plug Steel Pile**
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5. PRIORITY PARTICULARS OF THE APPLICATION (S) FILED IN CONVENTION COUNTRY

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Original (first) application number.	Date of filing of Original (first) application

8. PARTICULARS FOR FILING PATENT OF ADDITION

Main application/patent Number.	Date of filing of main application

9. DECLARATIONS:

(i) Declaration by the Inventor(s)

We, the above named inventors are the true & first inventors for this invention and declare that the applicant here in is our assignee or legal representative.

(a) Date 27th August, 2013
(b) Signature(s)
(c) Name (s) Naresh Kumar Ashutosh Trivedi

(ii) Declaration by the applicants in the convention country

We, the applicants in the convention country declare that the applicants herein are our assignee or legal representative.

(a) Date 27th August, 2013
(b) Signature(s)
(c) Name(s) of the signatory Naresh Kumar

GOVT. OF INDIA PATENT OFFICE
D. No. 14339
27 AUG 2013
BAUDHIK SAMPADA BHAWAN
NEW DELHI

(III) Declaration by the applicant(s):
We, the applicant(s) hereby declare(s) that: -

- ❑ We are in possession of the above-mentioned invention
- ❑ The complete specification relating to the invention is filed with this application.
- ❑ The invention as disclosed in the specification uses the biological material from India and the necessary permission from the competent authority shall be submitted by me/us before the grant of patent to me/us.
- ❑ There is no lawful ground of objection to the grant of the Patent to us.
- ❑ We are the assignee or legal representative of true & first inventors.
- ❑ The application or each of the applications, particulars of which are given in Para - 5 was the first application in convention country/countries in respect of our invention.
- ❑ We claim the priority from the above mentioned application(s) filed in convention country/countries and state that no application for protection in respect of the invention had been made in a convention country before that date by us or by any person from which We derive the title.
- ❑ our application in India is based on international application under Patent Cooperation Treaty **(PCT)** as mentioned in Para - 6.
- ❑ The application is divided out of our application particulars of which are given in Para - 7 and pray that this application may be treated as deemed to have been filed on ________under sec.16 of the Act.
- ❑ The said invention is an improvement in or modification of the invention particulars of which are given in Para- 8„

10. Following are the attachments with the application:

(a) Complete specification
(b) Complete specification (in conformation with the international application)/as amended before the International Preliminary Examination Authority (IPEA), as applicable (2 copies), No. of Pages 25 No. of claims 20
(c) Drawings (in conformation with the international application)/as amended before the International Preliminary Examination Authority (IPEA), as applicable (2 copies),No. of Sheets
(d) Priority documents
(e) Translation of priority document/Specification/International Search Report
(f) Statement and undertaking on Form 3
(g) Power of Authority
(h) Declaration of inventorship on Form 5
(i) Sequence listing in electronic form
(j) Form 9
(k) Form 18

Fee Rs 8000=00........ in Cash,/ Cheque / Bank Draft bearing no ....
Date 27/08/2013.......... on .... Bank.

We hereby declare that to the best of our knowledge, information and belief the fact and matters stated herein are correct and We request that a patent may be granted to us for the said invention.

Dated this Twenty Seventh day of August, 2013

To, The Controller of Patent
The Patent Office, at...Sector-14, Dwarka,
Boudhik sampada,PIN-110075
Delhi........

NARESH KUMAR ASHUTOSH TRIVEDI

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
30 October 2014 (30.10.2014)

WIPO | PCT

(10) **International Publication Number**
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(51) **International Patent Classification**:
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PCT/IN2014/000170

(22) **International Filing Date**:
18 March 2014 (18.03.2014)

(25) **Filing Language**: English

(26) **Publication Language**: English

(30) **Priority Data**:
1234/DEL/2013 26 April 2013 (26.04.2013) IN

(72) **Inventors; and**
(71) **Applicants** : **KUMAR, Naresh** [IN/IN]; Technological University, Opposite Sector-17, Rohini, Near Shahabad Daulatpur, Bawana Road., Delhi 110042 (IN). **TRIVEDI, Ashutosh** [IN/IN]; Technological University, Opposite Sector-17, Rohini, Near Shahabad Daulatpur, Bawana Road., Delhi 110042 (IN).

(74) **Common Representative**: **KUMAR, Naresh**; Technological University, Opposite Sector-17, Rohini, Near Shahabad Daulatpur, Bawana Road., Delhi 110042 (IN).

(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) **Title**: SLOTTED HOLES MESH FILTERED STEEL PILE

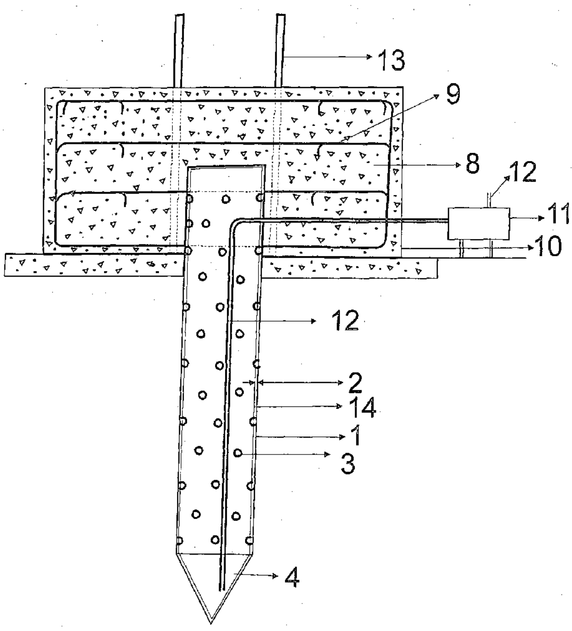


Fig 1 Slotted Holes Mesh- Filtered Steel Pile with Pile Cap

(57) **Abstract**: Described herein is a "Slotted Holes Mesh-Filtered Steel Pile" that can be used in a variety of soil conditions as well as apparatus and associated methods. Slotted holes helps in increase of effective stresses in soil-steel pile surface interaction by draining out extra buildup of pore water pressure in the immediate and longer run of time. As the potential flow of water will not be outwards but inwards t inside of steel pile through slotted holes of steel pile. It relieves of chances of buildup of excess pore water pressure for liquefaction of soils in the radially stressed zones of interaction of soil-steel pile.

WO 2014/174525 A3

Declarations under Rule 4.17:

— *as to the identity of the inventor (Rule 4.17(i))*

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

— *of inventorship (Rule 4.17(iv))*

Published:

— *with international search report (Art. 21(3))*

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

(88) Date of publication of the international search report: 26 March 2015

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IN2014/000170

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - E02D 3/10 (2015.01)
CPC - E02D 3/10 (2014.12)
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - E02D 3/10, 5/04, 5/24, 5/28, 19/10 (2015.01)
CPC - E02D 3/10, 5/00, 5/04, 5/22, 5/24, 5/285, 5/48, 19/10 (2014.12)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC - 175/314; 405/36, 43, 50, 231 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

PatBase, Google Patents, Google
Search terms used: post, pier, casing, column, pillar, pile, piling, spar, stanchion, steel, metal, water, liquid, fluid, ground, drain, seep, pump, mesh, screen, filter, plug

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	CN 202865828 U (WU) 10 April 2013 (10.04.2013) see machine translation	1-12, 14-17
Y	US 5,713,701 A (MARSHALL) 03 February 1998 (03.02.1998) entire document	1-12, 14-17
Y	US 4,260,284 A (HUART) 07 April 1981 (07.04.1981) entire document	1-12, 14-17
Y	GB 639,349 A (HANDEL et al) 28 June 1950 (28.06.1950) entire document	2, 9, 17
Y	JP 4-115011 A (TAKESHI et al) 15 April 1992 (15.04.1992) see abstract (English)	7, 11, 17
Y	US 2,864,241 A (FIORE et al) 16 December 1958 (16.12.1958) entire document	14
Y	GB 1,147,610 A (VAN BEVEREN) 02 April 1969 (02.04.1969) entire document	16
A	US 5,927,907 A (SHIRAISHI) 27 July 1999 (27.07.1999) entire document	1-17
A	US 4,124,982 A (FULLER) 14 November 1978 (14.11.1978) entire document	1-17

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
09 January 2015	21 JAN 2015

Name and mailing address of the ISA/US	Authorized officer:
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Espacenet

Bibliographic data: WO2015029054 (A1) — 2015-03-05

SLOTTED HOLES MESHED PLUG STEEL PILE

Inventor(s): KUMAR NARESH [IN]; TRIVEDI ASHUTOSH [IN] + (KUMAR, NARESH, ; TRIVEDI, ASHUTOSH)

Applicant(s): KUMAR NARESH [IN]; TRIVEDI ASHUTOSH [IN] + (KUMAR, NARESH, ; TRIVEDI, ASHUTOSH)

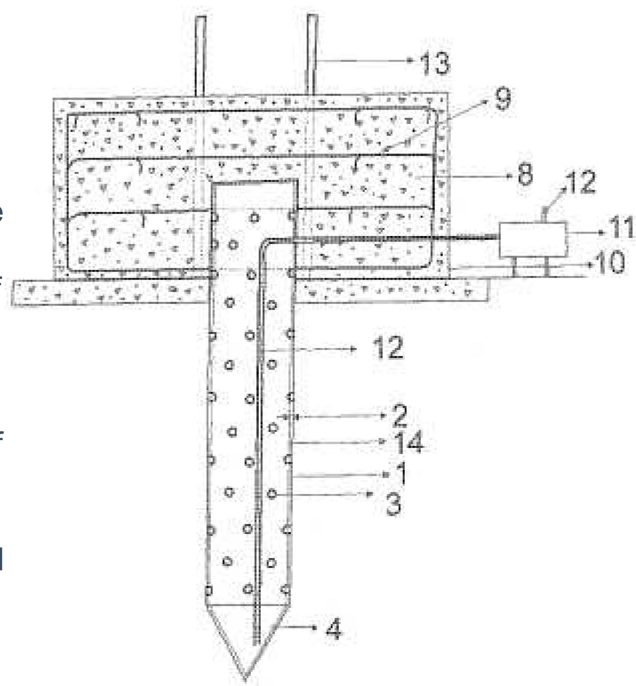
Classification: - **international:** *E02D3/10*
- **cooperative:** E02D3/10; E02D5/48

Application number: WO2014IN00171 20140318

Priority number(s): IN2013DE02524 20130827

Abstract of WO2015029054 (A1)

Described herein is a "Slotted Holes Meshed Plug Steel Pile" that can be used in a variety of soil conditions as well as apparatus and associated methods. Slotted holes helps in increase of effective stresses in soil-steel pile surface interaction by draining out extra buildup of pore water pressure in the immediate and longer run of time. As the potential flow of water will not be outwards but inwards to inside of steel pile through slotted holes of steel pile. It relieves of chances of buildup of excess pore water pressure for liquefaction of soils in the radially stressed zones of interaction of soil-steel pile.



Espacenet

Bibliographic data: WO2014174525 (A2) — 2014-10-30

SLOTTED HOLES MESH FILTERED STEEL PILE

Inventor(s):	KUMAR NARESH [IN]; TRIVEDI ASHUTOSH [IN] + (KUMAR, NARESH, ; TRIVEDI, ASHUTOSH)	
Applicant(s):	KUMAR NARESH [IN]; TRIVEDI ASHUTOSH [IN] + (KUMAR, NARESH, ; TRIVEDI, ASHUTOSH)	
Classification:	**- international:**	***E02D5/04***
	- cooperative:	**E02D5/04**
Application number:	WO2014IN00170 20140318	
Priority number(s):	IN2013DE01234 20130426	
Also published as:	WO2014174525 (A3)	

Abstract of WO2014174525 (A2)

Described herein is a "Slotted Holes Mesh- Filtered Steel Pile" that can be used in a variety of soil conditions as well as apparatus and associated methods. Slotted holes helps in increase of effective stresses in soil-steel pile surface interaction by draining out extra buildup of pore water pressure in the immediate and longer run of time. As the potential flow of water will not be outwards but inwards to inside of steel pile through slotted holes of steel pile. It relieves of chances of buildup of excess pore water pressure for liquefaction of soils in the radially stressed zones of interaction of soil-steel pile. As effective stresses are directly proportional to shear strength of the soil mass, thereby, it will lead to increase of side-resistance on soil-steel pile surfaces.; The side-resistance which is a part of load carrying capacity of steel piles will be increased to a large extent due to increase of effective stresses on soil-steel pile interface. This will be further increased due to presence of slotted holes on the outer lateral surface of the steel pile which not only drains out pore water to inside of the steel pile through mesh filter but also increase frictional forces due to roughness of the surface. In totality, it leads to increase in load carrying capacity of the pile, increase in the density of adjoining soil mass, consolidation of the soft soil and improved safety factor for

designed loads of super-structures. The dewatering unit attached through a pipe from the top-most slotted hole of the steel pile shall act to remove the drained out water collected in-side the slotted hole steel pile.; This special feature of slotted hole is provided throughout the vertical wall to accelerate the drainage in the entire zone of influence. A fine wire mesh of a designed sieve size is placed inside the slotted steel pile.

Publications in International Journals

1. Trivedi, A., Tanmay Banik, Tanay Sukumar, Naresh Kumar, Akshay Jain, and Amit Kumar. (2015). "Consolidation of clayey gouge amid permeating rock masses." Environmental Geotechnics, Volume 2, Issue 3, pages 137 –154. DOI: 10.1680/envgeo.13.00043
2. Trivedi, A., Tanmay Banik, Tanay Sukumar, Naresh Kumar, Akshay Jain, and Amit Kumar. (2015). Discussion: Consolidation of clayey gouge amid permeating rock masses. Environmental Geotechnics, Volume 2, Issue 4, December 2014 pages 237 –248. DOI: 10.1680/envgeo.14.00038

International Patents

1. Kumar N., and Trivedi A., (2014a) International PCT on Slotted Holes Meshed Plug Steel Pile .https://patents.google.com/patent/WO2015029054A1/en?q=slotted+holes&q=mesh&q=filtered&q=steel&q=pile
2. Kumar N., and Trivedi A., (2014b) International PCT on Slotted Holes Mesh Filtered Steel Pile. https://patents.google.com/patent/WO2014174525A2/en?q=slotted+holes&q=mesh&q=filtered&q=steel&q=pile

   Also published as,
3. Kumar N., and Trivedi A., (2015) International PCT on Slotted Holes Mesh Filtered Steel Pile. https://patents.google.com/patent/WO2014174525A3/en?q=slotted+holes&q=mesh&q=filtered&q=steel&q=pile

Indian Patents

1. Kumar N., and Trivedi A., (2013a) Indian Patent on Slotted Holes Mesh Filtered Steel Pile, 1234/Del/2013. ………Continued on next page.

2. Kumar N., and Trivedi A., (2013b) Indian Patent on Slotted Holes Meshed Plug Steel Pile, 2524/Del/2013.

Role of Special Feature in Side Resistance of a Model Steel Pile

Thesis Submitted to the University of Delhi

for the Award of the Degree of

Doctor of Philosophy

in

Civil Engineering

Submitted by

Naresh Kumar

(Ref. No FT / Ph.D. / 10241)

University of Delhi, Enrolment No.Ph.D. - 49/2009

Under the guidance of

Prof. (Dr.) A. Trivedi

Professor

Department of Civil Engineering

Faculty of Technology, University of Delhi

Department of Civil Engineering, Faculty of Technology

University of Delhi, Delhi

September 2015

Careful experimental studies should be done for changes in side-resistance of special featured model steel pile by varying the below mentioned parameters one by one and/or in combination of them for the followings parameters:

(i) By changing the geometrical shapes of holes.

(ii) By changing the diameter or dimensions of holes.

(iii) By changing the length of spikes.

(iv) By changing the spacing, vertical as well as horizontal, among the spikes.

(v) By changing the diameter of spikes.

(vi) By changing the geometrical shapes of spikes.

(vii) By forward or backward tapering of spikes.

(viii) By having spikes on spikes.

(ix) By changing the inclination of spikes, upwards or downwards.

(x) By using steel pipes as spikes.

(xi) By cutting the steel pipes diametrically along their length into halves as spikes and keeping these halves diametric open faces upwards or downwards.

(xii) By cutting the pipes diametrically along their length into halves and welding them diametrically opposite with their open faces, one upwards and the other downwards and using these welded pieces as spikes

(xiii) By using steel flats instead of spikes.

(xiv) By using forward camber in steel flats.

(xv) By using driven piles verses jacked piles.

(xvi) By changing diameter of outside fins.

(xvii) By changing upper and lower slope of fins.

(xviii) By making the plain lateral surface into a helical or screw threaded surface.

(xix) By using double cylindrical slotted steel shells spaced con-centrically and encapsulating the space with a graded filter of designed ratio of a mix of fine and coarse aggregates with or without spikes and that, too, with plain or corrugated surface of outer steel pile.

(xx) Wedge effect and gravity studies on account of entangled soil mass among the inclined spikes should be done for cohesive-friction soils.

(xxi) By using slotted holes mesh-filered spikes as patented by Kumar and Trivedi (2013 a).

(xxii) By using slotted holes mesh-plugged spikes as patented by Kumar and Trivedi (2013 b).