

Stability Analysis of Well Foundation During Cantilever Construction of segmental PSC Box Girder Bridge

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ABSTRACT

Well foundations (also known as caissons) are commonly used to support major bridges, particularly when building across rivers where the ground is very deep before reaching solid, stable layers. When segmental prestressed concrete (PSC) box girder bridges are built using the cantilever method, these foundations face a range of complex and changing loads that are quite different from what they will experience once the bridge is complete. The uneven forces that occur during the step-by-step construction process create important stability challenges that engineers need to consider carefully when designing and building the foundations.

In this thesis work, a complete stability analysis of the well foundation for segmental PSC box girder bridge construction using free cantilever technique has been carried out employing the STAAD.Pro structural analysis software. The analysis has been carried out for a pier-well foundation where the superstructure is built up using the balanced cantilever technique from the top of the pier. This analysis includes various cases of unbalanced loads such as (i) additional erection of one segment on one side, (ii) difference in concrete densities (left and right cantilever arm - 2.4 t/m³ and 2.6 t/m³ respectively), (iii) wind load on the partial cantilever, and (iv) live load on the additional segment erected on the unbalanced side only. The structural model comprises the pier cap, pier shaft, and well foundation members. Members 2 through 7 represent the diaphragm region, member 1 represents the left-side cantilever segment, and members 8 and 9 represent the two right-side segments creating the unbalance condition. The maximum segment weight is 84 tonnes with maximum depth of 5.5 m and soffit width of 5.5 m. The traveler (launching equipment) weight of 8.5 tonnes is also incorporated in the loading.

Base pressure, resultant eccentricity, overturning moment, and factor of safety against overturning and sliding are considered to analyze the structural stability of the footing. Data for the analysis is provided based on different load cases according to IRC and IS standards. It is found that the maximum eccentricity and critical state of overturning arise during the condition where right-side segment erection takes place along with density difference and wind loads.

LIST OF SYMBOLS, ABBREVIATIONS AND NOMENCLATURE

PSC	Prestressed Concrete
IRC	Indian Roads Congress
IS	Indian Standard
FOS	Factor of Safety
γ	Unit weight of concrete (t/m^3)
W	Total vertical load (kN or tonnes)
M	Moment ($\text{kN}\cdot\text{m}$ or $\text{t}\cdot\text{m}$)
e	Eccentricity of resultant (m)
q	Base pressure (t/m^2)
D	Diameter of well foundation (m)
L	Length/depth of well (m)
σ	Stress (kN/m^2)
P	Axial load (kN)
²² DL	Dead Load
LL	Live Load
WL	Wind Load
STAAD	Structural Analysis and Design
BOX	Box section girder
CG	Centre of Gravity
BM	Bending Moment ($\text{kN}\cdot\text{m}$)
SF	Shear Force (kN)
OTM	Overturning Moment
RM	Restoring Moment

CHAPTER 1 INTRODUCTION

1.1 General

Indian bridge construction technology has seen immense developments during the last few decades especially in relation to use of prestressed concrete segmental box girder bridges for construction of road and rail bridges over river and gorge crossings. The balanced cantilever method is a bridge construction technique where the superstructure is built outward segment by segment in both directions from a central pier. By adding segments symmetrically, the cantilevered arms remain balanced, allowing construction without temporary scaffolding underneath. Highly optimal for bridges with spans ranging from 50 to 250 meters.

Well foundation is also referred to as open caisson or box caisson. This is the most preferred type of foundation in the case of large bridges in India due to the success of well foundations in terms of their performance, ease of construction in wet sites, and load-bearing capacity.

When the free cantilever method of construction is undertaken, the pier and its foundations will be exposed to transient loadings which could be considerably more severe than the eventual loads under normal service. This is because of the sequential and asymmetrical manner in which the segments are placed, equipment loading, varying concrete densities, wind actions, and constructional loads. The stability of the well foundation in such construction states becomes a very important engineering problem.

1.2 Problem Statement

For the particular PSC box girder bridge, which is being taken into account, the process of erection through the Balanced Free Cantilever method is considered. During this erection process, the segments have to be arranged in such a way that symmetry exists around the pier. Nevertheless, symmetry is not achieved most of the time due to operation-related issues.

In this thesis, the particular problem that is examined entails an asymmetric situation whereby the right cantilever arm has an extra member (Members 8 and 9) to that of Member 1 in the left cantilever arm. Adding to the asymmetry is the use of concrete with two different densities (2.6 t/m^3 in the right and 2.4 t/m^3 in the left), as well as wind loads and the additional load in Member 8. The highest weight per segment is 84 tonnes while the traveler weight is 8.5 tonnes per side.

In the structural model, members 2 to 7 form the region representing the diaphragm (pier cap / cross head), which acts as the interface between the superstructure and the pier shaft. The main focus of the thesis involves the analysis of the resulting base pressure, eccentricity, and factor of safety for the caisson foundation in this unbalanced condition.

1.3 Objectives of the Study²¹

The main objectives of this research are:

- For the creation of an accurate three-dimensional finite element analysis model of the segmental pre-stressed concrete box girder bridge pier and well foundation in STAAD.Pro software.
- For the consideration of realistic load conditions in terms of all possible critical unbalanced loading conditions, which includes: additional segment loading on one side, variable concrete density, wind loads, and loading on the overhang segment..
- To study the structural behavior (bending moment, shear force, and axial force) acting on the base of the pier and well foundation due to each load condition.
- To determine the foundation pressure, eccentricity, overturning, and restoring moments under each load condition.
- To estimate the FOS against overturning and sliding for each critical load condition.

- To determine the most critical load condition and provide safe construction guidelines.

1.4 Scope of Work

The scope of this thesis is limited to:

- Only static structural analysis is done; no dynamic behavior is studied.
- Phase of construction with maximum unbalance — one extra piece on the right side.
- Well Foundation of circular section taken as a rigid body for stability calculations
- Lateral loads according to IRC:6-2017 (Road Bridges—Loads, Forces & Stresses) and IS:875 (Code of Practice for Design Loads for Buildings & Structures).

¹² CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The purpose of this chapter is to give a brief overview of literature related to well foundation, construction technique of PSC Box Girder Bridge using cantilever method, unbalanced load during construction, and analysis of stability.

2.2 Well Foundations

A well foundation is a deep, hollow cylindrical or rectangular caisson sunk into the ground to provide a stable, deep-water support for heavy structures. Commonly used for river bridges, it is favored over piles because its massive size resists scouring, floating debris, and heavy lateral loads. This type of foundation has found widespread application in Indian bridges for well over one hundred years now, with many instances seen on rivers like Ganga, Yamuna, and Brahmaputra.

A standard well foundation includes several key elements: Cutting Edge, Well Curb, Steining, Bottom/Top Plugs, Sand Filling, Well Cap.

The process of sinking a well involves careful, staged engineering, soil is excavated from inside the hollow well using mechanical grabs, allowing the structure to sink under its own massive weight. As the well sinks, additional concrete steining is built upward from the ground or water surface, maintaining the sinking process. Once the bedrock or a stable, load-bearing soil layer is reached, the bottom is sealed with concrete. The core is filled with sand, followed by the top plug and a well cap, creating a solid base to support the bridge pier.

Fundamental principles pertaining to bearing capacity and settlement of deep foundations have been established by Terzaghi & Peck (1967). Guidelines for well foundation for road bridges in India are available in IRC:78(part 1)-2024.

2.2.1 Load-Bearing Behaviour

The loading from the bridge superstructure is transmitted to the well foundation via the shaft of the pier. The well can take axial loads, lateral forces, and moments. The

bearing capacity of the well foundation will be affected by skin friction in the well shaft circumference, end bearing at the well bottom plug, and passive earth pressure at the slanted side of the well foundation.

In Mundrey's textbook on railway track engineering and bridge engineering (2009), he gives a detailed explanation of the behavior of well foundations under load combinations. He stresses that in construction phases, the eccentricity effect may dominate the design of foundations.

2.2.2 Stability Under Eccentric Loading

Well foundations subjected to eccentric and oblique loads have been widely studied. The traditional approach involves the use of an equivalent rectangle having smaller dimensions than those of the footing ($B' = B - 2e$), as suggested by Meyerhof (1963). In case of circular wells, effective area theory based on IS:3955 is applied.

Model experiments were done by Prakash & Saran (1971) concerning the behavior of piles under inclined loads. The results revealed that lateral loading considerably reduces the permissible capacity of the pile in terms of vertical loading.

2.3 Cantilever Construction of PSC Box Girder Bridges

In balanced cantilever method, instead of building the entire span at once or relying on ground supports (which are often impossible over deep rivers or highways), the bridge is constructed symmetrically using either precast segments or cast-in-place concrete. Form travelers, which are very heavy scaffolds, are used and placed on the cantilever constructed and proceed outward as the segments are formed or lifted into place. Requires no temporary supports or scaffolding in the space below, Highly efficient in materials for long-span applications, Faster construction sequence compared to traditional cast-in-place methods, Requires highly complex structural engineering and precision to control stresses and deflections during construction and Unbalanced loads or miscalculations during the segment erection process can risk structural failure.

In cantilever construction, instead of building the entire span at once or relying on ground supports (which are often impossible over deep rivers or highways), the bridge is constructed symmetrically using either precast segments or cast-in-place concrete. The Pier Segment: The very first segment (the diaphragm) is rigidly attached to the top of the pier. This prevents the structure from tipping during the building process. Segmental Addition: Special equipment (like a Form Traveler for cast-in-place or a launching gantry for precast segments) attaches a new segment on the left side, followed by a corresponding segment on the right side. Post-Tensioning: As each segment is added, high-strength steel tendons are threaded through the segment and tightened to secure the new piece to the existing structure, providing immense structural integrity. Closure: Once the cantilevers reach the required length, the gap between the two approaching arms (or the gap between adjacent piers) is sealed with a "drop-in" segment or a cast-in-place closure pour, effectively locking the spans together. It can be both cast-in-situ and precast.

2.3.1 Unbalanced Conditions During Construction

An unbalanced condition during cantilever bridge construction occurs when uneven loads (like heavy form travelers or unsymmetrical segment placements) cause critical overstressing, torsion, or pier tipping. To safely manage this, engineers rely on strict weight tracking, temporary clamping devices, and real-time structural monitoring.

As per perfect balance design for cantilever structures, the segments are placed equally on both sides of the pier, ensuring zero resultant moment on the pier top. Yet, according to the studies by Kumar et al. (2015), real-time construction records prove that temporary unbalanced conditions prevail quite often during normal construction activities.

The construction unbalance factors, as listed in previous literature surveys, consist of: (i) casting of one segment before its twin on the opposite side, (ii) placement or removal of form travelers, (iii) difference in concrete densities owing to variations in

mix ratios, (iv) loading from wind pressure on part-completed structure, (v) temperature effect, and (vi) creep and shrinkage effect.

Structural risk due to unbalanced condition are: Pier Overturning (If the unbalanced moment exceeds the designed capacity of the pier, it can cause the entire pier structure to tilt, crack, or fail.), Instability of the Superstructure: (Unequal loads can overstress the top or bottom slabs, causing cracking or structural deformation at the pier-segment interface.) ,Geometric Errors: (The bridge tip may deflect or twist out of alignment, making it impossible to correctly align and close the gap between cantilevers at mid-span).

2.4 Structural Analysis of Bridge Piers and Foundations

Presently, in the case of pier and foundation designs in bridges, the design depends on finite element analysis. The software known as STAAD.Pro has gained much popularity in the Indian scenario in the context of structural analysis of bridges. According to Chandra and Bose (2018), an analysis of bridge piers and foundations under seismic loading using STAAD.Pro is possible.

The IRC:6-2017 gives the necessary guidelines regarding load considerations for road bridges. According to the IRC:6-2017, the construction loads need to be treated as imposed loads with suitable impact factor consideration.

2.5 Gaps in Literature and Contribution of Present Study

Whereas there are a number of studies concerning the design of well foundations under the effects of service loads and seismic forces, very few papers have considered the cumulative effects of more than one unbalanced load during the erection phase of segmental cantilever construction.

The current paper fills this gap with an analysis conducted based on different loading situations as well as their combinations, considering real segment weights, real densities of concrete and other materials, and real weights of equipment involved in

the construction of a real bridge. In this study, the STAAD.Pro program takes into account the diaphragm (Members 2-7), the left cantilever (Member 1), and the right-side unbalanced segments (Members 8 and 9).

CHAPTER 3 METHODOLOGY

3.1 Overview of the Bridge

The bridge under consideration is a multi-span segmental PSC box girder bridge with spans supported on well foundations sunk through alluvial deposits to competent bearing strata. The superstructure consists of cast-in-situ segmental prestressed concrete box girders constructed using the free cantilever method with form travelers. The following key geometric and material parameters define the structure:

Parameter	Value	Unit
Maximum segment weight	84	tonnes
Maximum segment depth	5.5	m
Width of soffit (bottom flange)	5.5	m
Traveler (launching equipment) weight	8.5	tonnes
Concrete density – Left arm (Member 1)	2.4	t/m ³
Concrete density – Right arm (Members 8 & 9)	2.6	t/m ³
Number of left-side segments in model	1	(Member 1)
Number of right-side segments in model	2	(Members 8 and 9)
Diaphragm members	2–7	(6 members)

3.2 Structural Model Description

The STAAD Pro model includes the pier cap (Cross head), pier shaft, and well foundation as a Space frame structure. The numbering of members according to the scheme is shown below:

3.2.1 Member Numbering

- Members 1: Left cantilever arm – this comprises of only one member.
- Members 2 to 7: Diaphragm/Pier cap area – the superstructure load transfer takes place in this area. These members represent the Cross-head from where the superstructure load transfers to the pier.
- Member 8: First right-side member near the pier cap area.
- Member 9: Second right-side member (Outer most member creating the unbalance).

3.2.2 Node Definitions

In the case of the three-dimensional coordinate system, ²⁵the longitudinal axis of the ³bridge has been made along the X-axis, the transverse axis has been made along the Z-axis, while the vertical axis of the bridge has been made along the Y-axis. Gravity has been taken in the negative Y direction. The node number 1 has been assigned to the top of the pier cap.

3.3 Cross-Sectional Properties

The key sectional properties of the PSC box girder segment are:

Property	Left Segment (Member 1)	Right Seg. (Members 8,9)
Depth (m)	5.5	5.5
Soffit Width (m)	5.5	5.5
Concrete Density (t/m ³)	2.4	2.6

Property	Left Segment (Member 1)	Right Seg. (Members 8,9)
Unit Weight (kN/m ³)	24	26
Traveler Weight (t)	8.5	8.5

3.4 Load Cases for Unbalanced Construction Scenarios

The following are five basic load cases which represent all possible unbalanced conditions during cantilever construction. All the above load cases are superimposed based on load combination of IRC:6-2017 guidelines.

3.4.1 Load Case 1: Self Weight (Balanced Configuration)

This is the basic load case where there is symmetrical loading of both the arms of the structure having one element each side. Here, self-weight of all members is taken into account with density of left member 2.4t/m³ and density of the right member (member 8) equal to 2.6t/m³. Form Traveler weight of 8.5 tonnes is considered on outer nodes of the cantilevers.

Dead load from segment self-weight:

- Left arm (member 1): Self-weight calculation done using STAAD SELFWEIGHT command where unit weight is 23.54 kN/m³
- Right arm (member 8): Self-weight calculation done where unit weight is 25.51 kN/m³
- Traveler load: 8.5 t = 83.4 kN as concentrated load on tip nodes of both arms

3.4.2 Load Case 2: Additional Right Segment (Unbalanced DL)

This is an important stage during construction when there is an addition of only one section (Member 9) at the right-hand side with no addition of any member to the left-hand side. Here, there are two sections at the right-hand side (Members 8 and 9), and only one section at the left-hand side (Member 1). Additional dead load from Member 9: Self-weight using density 2.6 t/m³ = 25.51 kN/m³

- Shift of Traveler load to the tip of Member 9 (now the new outermost member): $8.5t = 83.4kN$
- Net unbalanced moment at pier cap = (Weight of Member 9 $\times$ Arm length of Member 9) + (Traveler weight $\times$ Shift of travel load)

The unbalanced moment caused by the added right-hand side member is the destabilizing load for which this thesis focuses on. It is equal to:

$$M_{unbal} = W_{seg9} \times L_{arm9} + W_{traveler} \times (L_{arm9} - L_{arm_left})$$

3.4.3 Load Case 3: Differential Density Load

This loading condition will specifically deal with the discrepancy created by the differential density in the two halves; the density in the left half being 2.4 t/m^3 whereas in the right half it is 2.6 t/m^3 . Despite the fact that there are equal numbers of segments on both sides, the heavier right half concrete segment results in creating a disparity.

- Density difference: $\Delta\gamma = 2.6 - 2.4 = 0.2 \text{ t/m}^3$
- Increase in specific weight in right: $0.2 \times 9.81 = 1.962 \text{ kN/m}^3$ (applied to right-side members only)
- Resulting extra moment = volume of right segments $\times 1.962 \text{ kN/m}^3 \times$ distance from center

3.4.4 Load Case 4: ²⁶Wind Load

Wind loads are considered on the partially erected bridge deck as per IS:875 Part 3 and IRC:6-2017 Clause 209. Area exposed to the wind is calculated considering depth and width of segments and pier.

Calculation of wind pressure:

- Design wind velocity at the site: V_z (to be determined from the IS:875 wind zone map – let us take Wind zone IV and $V_z = 47 \text{ m/s}$)
- Design wind pressure: $P_z = 0.6 \times V_z^2 \text{ N/m}^2 = 0.6 \times 47^2 = 1325 \text{ N/m}^2 = 1.325 \text{ kN/m}^2$

- Coefficient of wind pressure: $C_f = 1.3$ (box section having ratio of depth to width = 1.0 per IS:875 Table 25)
- Total force acting due to wind on the right segments (members 8 and 9):
 $F_{\text{wind}} = P_z \times C_f \times \text{exposed area}$
- The exposed area = Depth $\times$ Length of each segment = 5.5 m $\times$ (Length of each segment)
- The wind load is applied on the windward members as uniformly distributed load (UDL)

For stability analysis, wind velocity along the longitudinal bridge axis is critical since it causes an increase in overturning moment on the well foundation.

3.4.5 Load Case 5: Live Load on Additional Right Segment Only

This loading case is an illustration of loads due to personnel, equipment, and construction material that are imposed on Member 9 and have no loads applied on the other side.

- Construction live load : 4.8 kN/m²
- Area of application: Length of Member 9 $\times$ top surface width of box segment
- The top surface width of a two-lane box is generally 12.9 m, with the soffit width being 5.5 m
- Live load = $4.8 \times 12.9 \times (\text{length of Member 9})$
- A uniform load on the top flange of Member 9

3.5 Load Combinations

²⁴ Load combinations are as per IRC:6-2017 Table 1 and relevant construction stage provisions:

Combination	Description
101	Baseline Balanced DL Only
102	DL + Extra Right Segment
103	DL + Extra Segment + Traveler

Combination	Description
104	DL + Extra Segment + Traveler + Full Right LL
105	DL + Extra Segment + Traveler + Tip LL
106	DL + Extra Segment + Density Differential
107	DL + Density Differential + Traveler
108	DL + Extra Segment + Traveler + Wind Transverse
109	DL + Extra Segment + Traveler + Wind Longitudinal
110	DL + Extra Segment + Wind Transverse + Wind Longitudinal
111	DL + LL + Wind
112	Worst Case All Right Side Loads
113	Density Amplified Worst Case
114	Symmetric Comparison Case

3.6 Stability Analysis of Well Foundation

The stability of the well foundation is assessed through the following checks:

3.6.1 Base Pressure Calculation

For a circular well foundation of diameter D, the maximum and minimum base pressures under eccentric loading are computed as:

$$q_{\max} = (W/A) + (M/Z) \quad q_{\min} = (W/A) - (M/Z)$$

where W = total vertical load at the base, $A = \pi D^2/4$ = area of well base, M = total overturning moment at base, Z = section modulus = $\pi D^3/32$.

The allowable bearing capacity of the soil (q_{allow}) must not be exceeded, and $q_{\min}$ must remain positive (no tension at base).

3.6.2 Eccentricity Check

The resultant eccentricity at the base is:

$$e = M / W$$

For the foundation to remain stable (no tension at base), the resultant must lie within the 'core' of the foundation section. For a circular section of diameter D, the limiting eccentricity is $e \leq D/8$.

3.6.3 ¹Factor of Safety Against Overturning

The Factor of Safety (FOS) against overturning is defined as:

$$\text{FOS}_{\text{OT}} = \text{Restoring Moment} / \text{Overturning Moment} = (W \times D/2) / M_{\text{OT}}$$

Per IRC:78-2014, the minimum required FOS against overturning for well foundations during construction = 1.5 for temporary/construction loads.

3.6.4 ¹⁴Factor of Safety Against Sliding

The FOS against sliding at the base is:

$$\text{FOS}_{\text{SL}} = \mu \times W / H$$

¹⁴ where μ = coefficient of friction at base (typically 0.5 for soil-concrete), W = total vertical load, H = total horizontal force. Minimum required FOS against sliding = 1.5.

CHAPTER 4 STAAD.Pro MODELLING AND ANALYSIS.

4.1 Staad Pro input commands

STAAD SPACE 63+83+63 WITH TILTED WELL AND ECCENTRIC PIER 500
2000

UNIT METER MTON
JOINT COORDINATES

*superstructure nodes

1	142.9397	0	0
2	145.4397	0	0
3	145.9397	0	0
4	146.6897	0	0
5	147.4397	0	0
6	148.1897	0	0
7	148.9397	0	0
8	149.4397	0	0
9	151.9397	0	0
10	154.4397	0	0

*substructure nodes

11	147.4397	-5.5	0
12	147.4397	-6.474	0
13	147.4397	-7.448	0
14	147.4397	-8.422	0
15	147.4397	-9.396	0
16	147.4397	-10.37	0
17	147.4397	-11.344	0
18	147.4397	-12.318	0
19	147.4397	-13.292	0
20	147.4397	-14.266	0
21	147.4397	-15.24	0
22	147.4397	-17.5	0

*TILTED WELL NODES (COORDINATE OFFSET EMBEDDED)

23	147.0097	-17.5	-2
24	147.0577	-18.5	-1.9345
25	147.1057	-19.5	-1.8691
26	147.1537	-20.5	-1.8036
27	147.2017	-21.5	-1.7381
28	147.2497	-22.5	-1.6726
29	147.2977	-23.5	-1.6072
30	147.3457	-24.5	-1.5417
31	147.3937	-25.4999	-1.4762
32	147.4417	-26.4999	-1.4108
33	147.4897	-27.4999	-1.3453
34	147.5377	-28.4999	-1.2798
35	147.5857	-29.4999	-1.2144

36	147.6337	-30.4999	-1.1489
37	147.6817	-31.4999	-1.0834
38	147.7297	-32.4999	-1.0179
39	147.7777	-33.4999	-0.9525
40	147.8257	-34.4999	-0.887
41	147.8737	-35.4999	-0.8215
42	147.9217	-36.4999	-0.7561
43	147.9697	-37.4999	-0.6906
44	148.0177	-38.4999	-0.6251
45	148.0657	-39.4999	-0.5596
46	148.1137	-40.4999	-0.4942
47	148.1617	-41.4999	-0.4287
48	148.2097	-42.4999	-0.3632
49	148.2577	-43.4999	-0.2978
50	148.3057	-44.4999	-0.2323
51	148.3537	-45.4999	-0.1668
52	148.4017	-46.4999	-0.1014
53	148.4497	-47.4999	-0.0359
54	148.4977	-48.4999	0.0296
55	148.5457	-49.4999	0.0951
56	148.5937	-50.4999	0.1605
57	148.6417	-51.4999	0.226

MEMBER INCIDENCES

* Superstructure Girder Connectors

1 1 2 9

*LINK

10 5 11

*P1

11 11 12 21

*LINK

22 22 23

*P1 WELL

23 23 24 56

MEMBER PROPERTY INDIAN

* PIER HEAD PROPERTIES

2 TO 7 PRIS AX 9.804 IX 4.238 IY 71.056 IZ 45.687

*CANTILEVER CONSTRUCTION * VARIABLE DEPTH BOX GIRDER LEGS

1 8 PRIS AX 9.359 IX 3.78 IY 70.621 IZ 38.611

9 PRIS AX 8.916 IX 3.321 IY 70.053 IZ 32.46

*PIERS COLUMNS (RECTANGULAR PRISMATIC)

11 TO 20 PRIS YD 1.5 ZD 3.178

*LINK

10 22 PRIS AX 1000 IX 1000 IY 1000 IZ 1000

*WELL CAP

21 PRIS YD 8

* HOLLOW CIRCULAR WELL STEINING (STA = Outer Dia, THI = Wall Thickness)

23 TO 56 PRIS ROUND STA 8 END 8 THI 0.8

CONSTANTS

E 3.2E6 ALL

POISSON 0.17 ALL

ALPHA 12E-06 ALL

DENSITY 0.0 MEMB 1 TO 10 22

DENSITY 2.5 MEMB 11 TO 21 23 TO 56

SUPPORTS

33 FIXED BUT KFZ 6528 KFX 6532 KFY 100

34 FIXED BUT KFZ 8704 KFX 8704 KFY 100

35 FIXED BUT KFZ 10880 KFX 10880 KFY 100

36 FIXED BUT KFZ 13056 KFX 13056 KFY 100

37 FIXED BUT KFZ 15232 KFX 15232 KFY 100

38 FIXED BUT KFZ 17024 KFX 17024 KFY 100

39 FIXED BUT KFZ 19152 KFX 19152 KFY 100

40 FIXED BUT KFZ 21280 KFX 21280 KFY 100

41 FIXED BUT KFZ 27632 KFX 27632 KFY 100

42 FIXED BUT KFZ 30144 KFX 30144 KFY 100

43 FIXED BUT KFZ 32656 KFX 32656 KFY 100

44 FIXED BUT KFZ 29792 KFX 29792 KFY 100

45 FIXED BUT KFZ 31920 KFX 31920 KFY 100

46 FIXED BUT KFZ 34048 KFX 34048 KFY 100

47 FIXED BUT KFZ 40000 KFX 40000 KFY 100

48 FIXED BUT KFZ 42000 KFX 42000 KFY 100

49 FIXED BUT KFZ 44000 KFX 44000 KFY 100

50 FIXED BUT KFZ 48000 KFX 48000 KFY 100

51 FIXED BUT KFZ 50000 KFX 50000 KFY 100

52 FIXED BUT KFZ 52000 KFX 52000 KFY 100

53 FIXED BUT KFZ 55000 KFX 55000 KFY 100

54 FIXED BUT KFZ 60000 KFX 60000 KFY 100

55 FIXED BUT KFZ 90000 KFX 90000 KFY 100

56 FIXED BUT KFZ 100000 KFX 100000 KFY 100

57 FIXED BUT KMX 100000 KMZ 100000

*

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* LOAD DEFINITIONS CANTILEVER CONSTRUCTION STAGE

* BRIDGE 63+83+63

* Left arm : member 1 only (length 2.5 m, density 2.4 t/m3)

* Right arm : member 8 (2.5 m) + member 9 (3.0 m), density 2.6 t/m3

* Diaphragm : members 2-7 (pier head, density 2.5 t/m3)

* Traveller : 8.5 t at active tip

* Max seg wt: 84 t (all segments below this, no capping needed)

* Units : MTON, METER

*

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LOAD 1 DEAD LOAD BALANCED EXISTING STRUCTURE

* Diaphragm (pier head) members 2-7
 * UDL = $9.804 * 2.5 = 24.51$ t/m
 * Left arm member 1: $9.359 * 2.4 = 22.46$ t/m
 * Right arm member 8: $9.359 * 2.6 = 24.33$ t/m
 * Right arm member 9: $8.916 * 2.6 = 23.18$ t/m

3 SELFWEIGHT Y -1.0

MEMBER LOAD

2 TO 7 UNIGY -24.51

1 UNIGY -22.46

8 UNIGY -24.33

9 UNIGY -23.18

*

LOAD 2 UNBALANCED DL - EXTRA SEGMENT RIGHT TIP (MEMBER 9 ONLY)

* Weight = $8.916 * 3.0 * 2.6 = 69.55$ t

* UDL = $69.55 / 3.0 = 23.18$ t/m on member 9

* Left arm: NO extra segment

MEMBER LOAD

9 UNIGY -23.18

*

LOAD 3 FORM TRAVELLER - RIGHT TIP DURING CASTING OF MEMBER 9

* Traveller parked at node 10 (right tip) after casting member 9

* Weight = 8.5 t as point load at node 10

JOINT LOAD

10 FY -8.5

*

LOAD 4 FORM TRAVELLER - LEFT TIP

* Traveller parked at node 1 (left tip) after casting member 1

* Weight = 8.5 t as point load at node 1

JOINT LOAD

1 FY -8.5

*

LOAD 5 DENSITY DIFFERENTIAL - NET EFFECT RIGHT HEAVIER LEFT LIGHTER

* Right arm denser (2.6) vs Left arm (2.4) vs nominal (2.5)

* Net extra on right arm members (above nominal 2.5):

* Member 8: $(2.6-2.5) * 9.359 * 2.5 = +2.34$ t extra -> 0.936 t/m

* Member 9: $(2.6-2.5) * 8.916 * 3.0 = +2.67$ t extra -> 0.892 t/m

* Net relief on left arm members (below nominal 2.5):

* Member 1: $(2.4-2.5) * 9.359 * 2.5 = -2.34$ t relief -> +0.936 t/m (GY positive = upward)

* This LC used in combinations to amplify the existing right-heavy imbalance

MEMBER LOAD

8 UNI GY -0.936

9 UNI GY -0.892

1 UNI GY 0.936

*

LOAD 6 CONSTRUCTION LIVE LOAD - LEFT ARM MEMBER 1 (COMPARISON CASE)

* Used only in symmetric check combinations

* IRC 6: $4 \text{ kN/m}^2 = 0.4 \text{ t/m}^2$ construction live load

* Soffit width = 5.5 m (given)

* $w = 0.4 * 5.5 = 2.2 \text{ t/m}$

MEMBER LOAD

1 UNI GY -2.2

*

LOAD 7 LIVE LOAD ON OUTERMOST NEW SEGMENT ONLY (MEMBER 9 RIGHT TIP)

* Worst eccentricity: LL concentrated on outermost new segment only

* All construction activity (workers, material) at tip of member 9

* IRC 6: $4 \text{ kN/m}^2 = 0.4 \text{ t/m}^2$ construction live load

* Soffit width = 5.5 m (given)

* $w = 0.4 * 5.5 = 2.2 \text{ t/m}$

MEMBER LOAD

9 UNI GY -2.2

*

LOAD 8 WIND LOAD TRANSVERSE - Z DIRECTION (IRC 6 CL.209)

* Site: Lucknow, Wind zone IV

* $V_b = 47 \text{ m/s}$, $k_1 = 1.0$, $k_2 = 0.87$ (terrain cat 2, ht ~20m), $k_3 = 1.0$

* Design speed $V_z = 47 * 1.0 * 0.87 * 1.0 = 40.89 \text{ m/s}$

* Design pressure $P_z = 0.6 * 40.89^2 / 1000 = 1.003 \text{ kN/m}^2 = 0.1003 \text{ t/m}^2$

* Exposed girder depth = 5.5 m (max segment depth, given)

* Shape factor $C_f = 1.3$ (box girder, IRC 6 Table 5)

* Wind force per metre = $0.1003 * 5.5 * 1.3 = 0.718 \text{ t/m} \sim 0.72 \text{ t/m}$

* Pier shaft (members 11-20): exposed face = 3.178 m, $C_f = 0.7$

* Wind/m on pier = $0.1003 * 3.178 * 0.7 = 0.223 \text{ t/m} \sim 0.22 \text{ t/m}$

MEMBER LOAD

1 UNI GZ -0.72

2 TO 7 UNI GZ -0.72

8 UNI GZ -0.72
9 UNI GZ -0.72
11 TO 20 UNI GZ -0.22

*

LOAD 9 WIND LOAD LONGITUDINAL - X DIRECTION (25% OF TRANSVERSE)

* IRC 6 Cl. 209.3: longitudinal wind = 25% of transverse on deck
* Deck members: $0.25 * 0.72 = 0.18$ t/m
* Pier members: $0.25 * 0.22 = 0.055$ t/m ~ 0.06 t/m
* Traveller at right tip (node 9):
* Projected area = depth(5.5) * width(5.5) = 30.25 m²
* $F_{\text{transverse}} = 0.1003 * 30.25 * 1.2 = 3.64$ t
* $F_{\text{longitudinal}} = 0.25 * 3.64 = 0.91$ t at node 9

MEMBER LOAD

1 UNI GX -0.18
2 TO 7 UNI GX -0.18
8 UNI GX -0.18
9 UNI GX -0.18
11 TO 20 UNI GX -0.06

JOINT LOAD

9 FX -0.91

*

*** LOAD COMBINATIONS (IRC 6 / IS 875 Part 5 limit state)**

* Partial safety factors:
* DL (unfavourable) = 1.35
* Extra segment DL = 1.75 (construction, unbalanced)
* Live load = 1.50
* Density diff = 1.35
* Wind = 0.90 (when combined with DL+LL)
* = 1.20 (wind dominant, no live load)
*

LOAD COMBINATION 101

*DL + EXTRA SEGMENT RIGHT
1 1.35 2 1.75

LOAD COMBINATION 102

*DL + EXTRA SEGMENT RIGHT + DENSITY DIFF
* Core unbalanced construction check
* Right: 2 segments (8+9) vs Left: 1 segment (1)
1 1.35 2 1.75 5 1.35

LOAD COMBINATION 103

*DL + EXTRA SEGMENT + DENSITY DIFF + TRAVELLER RIGHT

* Traveller at right tip while casting member 9

1 1.35 2 1.75 5 1.35 3 1.5

LOAD COMBINATION 104

*DL + EXTRA SEGMENT + DENSITY DIFF + TRAVELLER RIGHT + LL

* All right-side construction loads active simultaneously

1 1.35 2 1.75 5 1.35 3 1.5 7 1.5

LOAD COMBINATION 105

*DL + EXTRA SEGMENT + DENSITY DIFF + TRAVELLER RIGHT + LL +
WIND (MOST CRITICAL)

* LL concentrated on new outermost segment - worst moment arm

1 1.35 2 1.75 5 1.35 3 1.5 7 1.5 8 0.9 9 0.9

PERFORM ANALYSIS

PRINT MEMBER FORCES LIST 10 22

* Check force transfer through link members to well top

PRINT SUPPORT REACTIONS

* Key output: lateral reactions at soil spring nodes 33-57

* Compare KFX and KFZ spring forces against allowable soil pressure

PRINT JOINT DISPLACEMENT LIST 5 11 22 23

* Node 5 = pier cap level

* Node 11 = pier base / well cap top

* Node 22 = well cap bottom / steining top

* Node 23 = first tilted well node

* Track lateral displacement to quantify well tilt under each combo

FINISH



Nodes



3D view

4.2 Model Geometry and Node Coordinates

The three-dimensional structural model is created in STAAD.Pro with the following geometry. All coordinates are in metres.

Node No.	X (m)	Y (m)	Z (m)	Description
57	148.6417	-51.4999	0.226	Well base centre (FIXED support)
23	147.0097	-17.5	-2	Top of well / base of pier
11	147.4397	-5.5	0	Top of pier / bottom of pier cap

1	142.9397	0	0	Left end of pier cap / anchor of Mem 1
5	147.4397	0	0	Centre of pier cap (top)
9	151.9397	0	0	Junction Mem 8 & 9
10	154.4397	0	0	Tip of Mem 9 (right tip)

4.3 Member Connectivity

Member No.	Start Node	End Node	Element Type	Description
1	1	2	BEAM	Left cantilever segment
2	2	3	BEAM	Diaphragm – longitudinal
3	3	4	BEAM	Diaphragm – cross member
4	4	5	BEAM	Diaphragm – cross member
5	5	6	BEAM	Diaphragm – cross member
6	6	7	BEAM	Diaphragm – longitudinal
7	7	8	BEAM	Diaphragm to pier connection
8	8	9	BEAM	First right cantilever segment
9	9	10	BEAM	Additional right segment (unbalanced)
12	11	12	BEAM	Pier shaft start
23	23	24	BEAM	Well foundation start

4.4 Section Properties in STAAD.Pro

Section properties are defined using STAAD's PRISMATIC or DEFINE SECTION commands. For the PSC box girder segments, a hollow rectangular section is used. The section properties are calculated based on the geometric dimensions of the box section.

4.5.1 Input Commands for Member Properties

MEMBER PROPERTY

* Left segment (Member 1) – density 2.4 t/m³

1 PRIS YD 5.5 ZD 5.5 YB 4.0 ZB 4.0

* Right segments (Members 8, 9) – density 2.6 t/m³

8 9 PRIS YD 5.5 ZD 5.5 YB 4.0 ZB 4.0

*(YD and ZD = outer dimensions, YB and ZB = inner void dimensions)

4.5 Support Conditions

Well foundation Node 57 is treated as a fixed but support, which only provides restraint to only the 3 degrees of freedom FX FY FZ and allowing MX MY and MZ. The foundation of the well at the base assumes that the entire structure is completely restrained at the point of rest on the founding stratum.

4.6 Material Properties

Material	E (kN/m ²)	Poisson's Ratio	Density (t/m ³)	Applied to
Concrete M40 (Left)	3.16×10 ⁷	0.2	2.4	Member 1
Concrete M40 (Right)	3.16×10 ⁷	0.2	2.6	Members 8, 9
Concrete M40 (General)	3.16×10 ⁷	0.2	2.6	Members 2–7, 11, 56

4.7 Load Input in STAAD.Pro

4.7.1 Self Weight

11
LOAD 1 LOADTYPE DEAD TITLE 'SELF WEIGHT' SELFWEIGHT Y -1

4.7.2 Traveler Loads (Load Case 2 – Unbalanced)

²⁷
LOAD 2 LOADTYPE DEAD TITLE 'TRAVELER AND ADDITIONAL
SEGMENT' * Traveler at tip of Member 9 (right) = 8.5 t = 83.4 kN downward
JOINT LOAD 7 FY -83.4 * Member 9 self weight (density 2.6) automatically
included via SELFWEIGHT

4.7.3 Differential Density Load (Load Case 3)

LOAD 3 LOADTYPE DEAD TITLE 'DENSITY DIFFERENCE LOAD' *
Additional UDL on right members for density difference ($0.2 \text{ t/m}^3 = 1.962 \text{ kN/m}^3$) *
Member 8: 0.936 t/m | Member 9: 0.892 t/m (net relief on Member 1: +0.936 t/m)
MEMBER LOAD 8 UNI GY -0.936 9 UNI GY -0.892 1 UNI GY 0.936

4.7.4 Wind Load (Load Case 4)

¹¹
LOAD 4 LOADTYPE WIND TITLE 'WIND ON RIGHT CANTILEVER' * Wind
pressure = 1.325 kN/m², $C_f = 1.3$ * Wind force per unit length = $1.325 \times 1.3 \times 5.5 =$
9.484 kN/m MEMBER LOAD 8 9 UNI GX 9.484

4.7.5 Construction Live Load on Member 9 (Load Case 5)

LOAD 5 LOADTYPE LIVE TITLE 'CONSTRUCTION LL ON MEMBER 9' * LL
= 4.8 kN/m², applied over top width (approx 10.5 m) * Load per unit length = $4.8 \times$
10.5 = 50.4 kN/m MEMBER LOAD 9 UNI GY -50.4

4.8 Load Combinations in STAAD.Pro

¹
LOAD COMBINATION 101 1 1.35 2 1.75

¹
LOAD COMBINATION 102 1 1.35 2 1.75 5 1.35

LOAD COMBINATION 103 1 1.35 2 1.75 5 1.35 3 1.5

LOAD COMBINATION 104 1 1.35 2 1.75 5 1.35 3 1.5 7 1.5

LOAD COMBINATION 105 CRITICAL 1 1.35 2 1.75 5 1.35 3 1.5 7 1.5 8 0.9 9 0.9

4.9 STAAD.Pro Analysis Output File

4.9.1 Problem Statistics

6
NUMBER OF JOINTS 57 NUMBER OF MEMBERS 56
NUMBER OF PLATES 0 NUMBER OF SOLIDS 0
6
NUMBER OF SUPPORTS 25 TOTAL DEGREES OF FREEDOM = 266
TOTAL PRIMARY LOAD CASES 9 TOTAL LOAD COMBINATION CASES = 5
13
SOLVER: OUT-OF-CORE BASIC SOLVER (64-bit) BAND-WIDTH= 6/2/18 DOF
SIZE OF STIFFNESS MATRIX = 5 DOUBLE KILO-WORDS REQRD/AVAIL. DISK SPACE =
12.2/182248.1 MB

4.9.2 Member End Forces – Members 10 and 22 (Units: MTON, METRE)

Member 10 connects Node 5 (pier cap centre) to Node 11 (pier base). Member 22 connects Node 22 (well cap bottom) to Node 23 (first tilted well node). All values in MTON and metres, local axes.

Member 10 – Link (Pier Cap to Pier Base)

LOAD	JT	AXIAL	SHR-Y	SHR-Z	TORSION	MOM-Y	MOM-Z
1	5	272.96	-0.00	0.00	0.00	-0.00	-348.41
	11	-272.96	0.00	-0.00	-0.00	-0.00	348.41
2	5	57.95	-0.00	0.00	0.00	-0.00	-333.21
	11	-57.95	0.00	-0.00	-0.00	-0.00	333.21
3	5	8.50	-0.00	0.00	0.00	-0.00	-59.50
	11	-8.50	0.00	-0.00	-0.00	-0.00	59.50
4	5	8.50	0.00	0.00	0.00	-0.00	38.25
	11	-8.50	-0.00	-0.00	-0.00	-0.00	-38.25
5	5	2.23	-0.00	0.00	0.00	-0.00	-28.03
	11	-2.23	0.00	-0.00	-0.00	-0.00	28.03
6	5	5.50	0.00	0.00	0.00	-0.00	17.87
	11	-5.50	-0.00	-0.00	-0.00	-0.00	-17.87
7	5	5.50	-0.00	0.00	0.00	-0.00	-31.63
	11	-5.50	0.00	-0.00	-0.00	-0.00	31.63
8	5	-0.00	-0.00	-8.28	-10.35	0.00	-0.00
	11	0.00	0.00	8.28	10.35	45.54	0.00
9	5	0.00	-2.98	0.00	0.00	-0.00	0.00
	11	-0.00	2.98	-0.00	-0.00	-0.00	-16.39
101	5	469.92	-0.00	0.00	0.00	-0.00	-1053.47
	11	-469.92	0.00	-0.00	-0.00	-0.00	1053.47
102	5	472.93	-0.00	0.00	0.00	-0.00	-1091.32
	11	-472.93	0.00	-0.00	-0.00	-0.00	1091.32
103	5	485.68	-0.00	0.00	0.00	-0.00	-1180.57
	11	-485.68	0.00	-0.00	-0.00	-0.00	1180.57
104	5	493.93	-0.00	0.00	0.00	-0.00	-1228.01
	11	-493.93	0.00	-0.00	-0.00	-0.00	1228.01
105	5	493.93	-2.68	-7.45	-9.32	0.00	-1228.01
	11	-493.93	2.68	7.45	9.32	40.99	1213.25

Member 22 – Well Cap Bottom to First Tilted Well Node

LOAD	JT	AXIAL	SHR-Y	SHR-Z	TORSION	MOM-Y	MOM-Z
1	22	-0.00	-673.04	-0.00	340.62	-0.00	73.23
	23	0.00	673.04	0.00	-340.62	0.00	-1450.07
2	22	-0.00	-57.95	-0.00	325.77	-0.00	70.04
	23	0.00	57.95	0.00	-325.77	0.00	-188.59
3	22	-0.00	-8.50	-0.00	58.17	-0.00	12.51
	23	0.00	8.50	0.00	-58.17	0.00	-29.89

4	22	-0.00	-8.50	0.00	-37.40	0.00	-8.04
	23	0.00	8.50	-0.00	37.40	-0.00	-9.35
5	22	-0.00	-2.23	-0.00	27.41	-0.00	5.89
	23	0.00	2.23	0.00	-27.41	0.00	-10.45
6	22	-0.00	-5.50	0.00	-17.48	0.00	-3.76
	23	0.00	5.50	-0.00	17.48	-0.00	-7.49
7	22	-0.00	-5.50	-0.00	30.92	-0.00	6.65
	23	0.00	5.50	0.00	-30.92	0.00	-17.90
8	22	10.19	0.00	2.19	33.67	10.35	-156.60
	23	-10.19	-0.00	-2.19	-33.67	-14.83	156.60
9	22	0.75	-0.00	-3.48	-55.06	0.00	-11.84
	23	-0.75	0.00	3.48	55.06	7.13	11.84
101	22	-0.00	-1010.02	-0.00	1029.94	-0.00	221.43
	23	0.00	1010.02	0.00	-1029.94	0.00	-2287.63
102	22	-0.00	-1013.03	-0.00	1066.94	-0.00	229.39
	23	0.00	1013.03	0.00	-1066.94	0.00	-2301.74
103	22	-0.00	-1025.78	-0.00	1154.19	-0.00	248.15
	23	0.00	1025.78	0.00	-1154.19	0.00	-2346.58
104	22	-0.00	-1034.03	-0.00	1200.57	-0.00	258.12
	23	0.00	1034.03	0.00	-1200.57	0.00	-2373.43
105	22	9.85	-1034.03	-1.16	1181.32	9.32	106.52
	23	-9.85	1034.03	1.16	-1181.32	-6.93	-2221.84

4.9.3 Support Reactions – Key Nodes (Units: MTON, METRE)

Soil spring nodes 33–56 provide lateral restraint; Node 57 is the fixed well base. Reactions for Node 33 (topmost spring) and Node 57 (well base) are shown in full. All units MTON and metres.

Node 33 – Topmost Soil Spring

LOAD	FX	FY	FZ	MOM=X	MOM=Y	MOM=Z
1	-0.21	0.07	-0.29	-719.34	-0.00	178.32
101	-0.30	0.10	-0.41	-1104.22	-0.00	816.35
102	-0.30	0.10	-0.41	-1108.17	0.00	853.97
103	-0.30	0.10	-0.41	-1124.90	0.00	942.28
104	-0.30	0.10	-0.41	-1135.73	0.00	989.11
105	-0.30	0.10	-0.41	-893.07	-4.41	904.74

Node 57 – Well Base (Fixed Support)

LOAD	FX	FY	FZ	MOM=X	MOM=Y	MOM=Z
1	11.53	2215.27	15.72	1.19	-0.00	-0.87
101	16.17	3091.97	22.05	1.66	-0.00	-1.22
102	16.19	3094.98	22.08	1.67	-0.00	-1.22
103	16.26	3107.73	22.18	1.67	-0.00	-1.23
104	16.31	3115.97	22.25	1.68	-0.00	-1.23
105	19.51	3115.97	31.60	1.75	0.10	-1.25

4.9.4 Joint Displacements – Key Nodes (Units: cm, Radians)

Node 5 = pier cap level; Node 11 = pier base / well cap top; Node 22 = well cap bottom / steining top; Node 23 = first tilted well node. Lateral displacements track well tilt under each combination.

Node 5 – Pier Cap Level

LOAD	X-TRANS	Y-TRANS	Z-TRANS	X-ROTAN	Y-ROTAN	Z-ROTAN
1	1.2627	-0.1116	0.0688	0.0000	-0.0000	-0.0012
101	3.8051	-0.1643	0.1031	0.0000	0.0000	-0.0036
102	3.9413	-0.1647	0.1034	0.0000	0.0000	-0.0038
103	4.2628	-0.1664	0.1047	0.0000	0.0000	-0.0041
104	4.4336	-0.1675	0.1055	0.0000	0.0000	-0.0042

105 4.3196 -0.1666 0.0232 -0.0000 0.0000 -0.0041

Node 11 – Pier Base / Well Cap Top

LOAD	X=TRANS	Y=TRANS	Z=TRANS	X=ROTAN	Y=ROTAN	Z=ROTAN
1	0.6026	-0.1115	0.0529	0.0000	-0.0000	-0.0012
101	1.8111	-0.1642	0.0793	0.0000	0.0000	-0.0036
102	1.8758	-0.1646	0.0795	0.0000	0.0000	-0.0038
103	2.0285	-0.1664	0.0805	0.0000	0.0000	-0.0041
104	2.1096	-0.1675	0.0811	0.0000	0.0000	-0.0042
105	2.0504	-0.1665	0.0354	-0.0000	0.0000	-0.0041

Node 22 – Well Cap Bottom / Steining Top

LOAD	X=TRANS	Y=TRANS	Z=TRANS	X=ROTAN	Y=ROTAN	Z=ROTAN
1	0.0088	-0.0897	0.0184	0.0000	-0.0000	-0.0000
101	0.0201	-0.1281	0.0273	0.0000	0.0000	-0.0000
102	0.0206	-0.1283	0.0274	0.0000	0.0000	-0.0000
103	0.0218	-0.1292	0.0277	0.0000	0.0000	-0.0000
104	0.0225	-0.1297	0.0279	0.0000	0.0000	-0.0000
105	0.0216	-0.1288	0.0251	0.0000	0.0000	-0.0000

Node 33 – First Tilted Well Node

LOAD	X=TRANS	Y=TRANS	Z=TRANS	X=ROTAN	Y=ROTAN	Z=ROTAN
1	0.0089	-0.0834	0.0184	0.0000	-0.0000	-0.0000
101	0.0201	-0.1180	0.0273	0.0000	0.0000	-0.0000
102	0.0206	-0.1182	0.0274	0.0000	0.0000	-0.0000
103	0.0218	-0.1188	0.0277	0.0000	0.0000	-0.0000
104	0.0225	-0.1193	0.0279	0.0000	0.0000	-0.0000
105	0.0215	-0.1195	0.0251	0.0000	0.0000	-0.0000

17 CHAPTER 5 RESULTS AND DISCUSSION

5.1 Introduction

The findings of the analysis conducted for the well foundation system subjected to the different load cases and load combinations in Chapter 3 using the STAAD.Pro software are provided in this chapter. These findings are grouped according to (i) member forces in the pier and well foundation, (ii) reaction forces at the well base, (iii) base pressure computations, (iv) eccentricity of the resultant force, and (v) safety factors against overturning and sliding.

5.2 STAAD.Pro Output: Base Reactions

The critical output for well foundation stability is the reaction at the well base (Node 57 support). STAAD.Pro provides reactions as: FX (horizontal longitudinal), FY (vertical), FZ (horizontal transverse), MX, MY, MZ (moments about respective axes).

Load & load Combination	8 FX (MTON)	FY (MTON)	FZ (MTON)	MX (MTON- m)	MZ (MTON- m)
1	11.53	2215.27	15.72	1.19	-0.87
2	0.35	57.92	0.47	0.03	-0.02
3	0.05	8.50	0.07	0.00	0.00
4	0.05	8.50	0.07	0.00	0.00
5	0.01	2.23	0.02	0.00	0.00
6	0.03	5.50	0.04	0.00	0.00
7	0.03	5.50	0.04	0.00	0.00
8	0.00	0.00	10.39	0.08	0.00
9	3.56	0.00	0.00	0.00	-0.03
101	16.17	3091.97	22.05	1.66	-1.22
102	16.19	3094.98	22.08	1.67	-1.22

Load & load Combination	⁸ FX (MTON)	FY (MTON)	FZ (MTON)	MX (MTON- m)	MZ (MTON- m)
103	16.26	3107.73	22.18	1.67	-1.23
104	16.31	3115.97	22.25	1.68	-1.23
105	19.51	3115.97	31.60	1.75	-1.25

Table 5.1: STAAD.Pro Base Reactions at Well Foundation for All Load Cases and Combinations

5.3 Base Pressure Calculations

The base pressures at the well foundation are calculated using the formulae defined in Section 3.6.1. Assuming a circular well foundation of diameter D (to be specified from project data):

Load Combination	Vertical Load W (MTON)	Moment M (MTON-m)	Eccentricity e (m)	Status
101	3091.97	2287.63	0.74	SAFE
102	3094.98	2301.74	0.74	SAFE
103	3107.73	2346.58	0.76	SAFE
104	3115.97	2373.43	0.76	SAFE
105	3115.97	2221.84	0.71	SAFE

Table 5.2: Base Pressure and Eccentricity for Load Combinations

Maximum eccentricity:

- 0.76 m (Load Combination 103 and 104)

5.4 Eccentricity Analysis

The eccentricity of the resultant load at the well base is the key indicator of foundation stability. For a circular well of diameter D, the limiting eccentricity (to avoid tensile stress at the base) is $e_{lim} = D/8$.

From the results table above:

- Load Combination 101 (DL + Extra Segment Right): $e = 0.74 \text{ m}$, $D/8 = 8.0/8 = 1.0 \text{ m} \rightarrow \text{SAFE}$ ($e < 1.0 \text{ m}$)
- Load Combination 102 (DL + Extra Segment + Density Differential): $e = 0.74 \text{ m} \rightarrow \text{SAFE}$ ($e < 1.0 \text{ m}$)
- Load Combination 103 (DL + Extra Segment + Density Diff + Traveller): $e = 0.76 \text{ m} \rightarrow \text{SAFE}$ ($e < 1.0 \text{ m}$)
- Load Combination 104 (DL + Extra Segment + Density Diff + Traveller + LL): $e = 0.76 \text{ m} \rightarrow \text{SAFE}$ ($e < 1.0 \text{ m}$). Maximum eccentricity case.
- Load Combination 105 (Critical - All Loads + Wind): $e = 0.71 \text{ m} \rightarrow \text{SAFE}$ ($e < 1.0 \text{ m}$). All eccentricities are within $D/8 = 1.0 \text{ m}$. No tensile stress at well base under any construction combination.

5.5 Factor of Safety Against Overturning

The FOS against overturning for each load combination is computed from the well base reactions. The minimum required FOS for construction stages as per IRC:78(part 1)-2024 is 1.5.

Load Combination	W (MTON)	M (MTON-m)	FOS Against Overturning	Status
101	3091.97	2287.63	5.41	SAFE
102	3094.98	2301.74	5.38	SAFE
103	3107.73	2346.58	5.30	SAFE
104	3115.97	2373.43	5.25	SAFE
105	3115.97	2221.84	5.61	SAFE

Table 5.3: Factor of Safety Against Overturning

Minimum FOS:

- 5.25 (Load Combination 104)

IRC minimum required:

- 1.5

Hence all cases are SAFE.

5.6 Factor of Safety Against Sliding

The FOS against sliding is computed using $\mu = 0.5$ (concrete on soil) and the total horizontal force at the well base.

Load Combination	Vertical Load W (MTON)	Resultant H = $\sqrt{F_x^2 + F_z^2}$ at Node 57 (MTON)	FOS Against Sliding	Status
101	3091.97	27.34	56.54	SAFE
102	3094.98	27.38	56.52	SAFE
103	3107.73	27.50	56.50	SAFE
104	3115.97	27.59	56.47	SAFE
105	3115.97	37.14	41.95	SAFE

Table 5.4: Factor of Safety Against Sliding

The factor of safety against sliding was extremely high because:

- The foundation self-weight is very large,
- Horizontal wind loads are comparatively small,
- And the well foundation provides substantial resistance against lateral movement.

5.7 Critical Load Combination Identification and Explanation

Based on the results of the analysis performed, the critical load combination is the combo-104 where the load combination is Dead Load, Additional Right Segment, Differential Density, Traveller Load, and Construction Live Load on Member 9. This load combination creates the maximum overturning moment (2373.43 MTON-m) and minimum factor of safety against overturning (5.25). Load Combination 105, which additionally includes wind loads, produces a lower resultant overturning

moment at the well base (2221.84 MTON-m) because the wind-induced lateral forces partially counteract the eccentric vertical loading effect at the well foundation level.

Contribution of Each Load Component to Total Overturning Moment:

- Right side additional segment (Member 9, 84 t): This represents the primary cause of an unbalanced moment, since the vertical force of 84 t = 823.7 kN, exerted at the centroid, results in the formation of moment $823.7 \times \text{distance}$ from the centroid.
- Differential density ($\Delta\gamma = 0.2 \text{ t/m}^3$): Although it does not have much significance in the absolute terms, it should be noted that the differential density effect influences the design of the foundation by accumulating along the total length of the two segments (Members 8 and 9).
- Wind loading ($1.325 \text{ kN/m}^2 \times 1.3 \times 5.5 \text{ m}$): Wind forces create additional horizontal shear for sliding purposes and an additional overturning moment due to the height of the centroid of the exposed wind section above the well bottom.
- Construction live load on (Member 9): It adds further eccentric load at the outer-right edge.

It was found out that the differential density effect (Load Case 3) always increases foundation eccentricity due to heavier concrete in the right segment, regardless of whether the same number of segments is used on either side.

²⁰ CHAPTER 6 CONCLUSION AND FUTURE SCOPE

6.1 Conclusions

The conclusions that can be arrived at from the stability analysis of the well foundation for cantilever construction of the segmental precast concrete box girder bridge are as follows:

- An additional segment to the right side of the structure results in unbalanced loading, which acts as the main destabilizing load due to the eccentricities developed at the bottom of the well foundation.
- The difference in concrete density of 2.6 ¹⁵ t/m³ on the right side and 2.4 ¹⁵ t/m³ on the left side tends to increase the overturning effect, and therefore, construction crews have to exercise high-quality control to avoid such differences.
- Loading from the wind tends to create a horizontal shear force at the base as well as an overturning effect.
- The combination of load (Combo-104) where Dead Load, Additional Right Segment, Differential Density, Traveller Load, and Construction Live Load act together simultaneously will determine the design of the well foundation for the construction period. The minimum FOS against overturning under this critical combination is 5.25, which is well above the IRC:78-2014 minimum requirement of 1.5, confirming adequate safety for the construction stage.
- The eccentricity check for the critical load combination is passing. Maximum eccentricity $e = 0.76$ m (LC 103 and LC 104) is well within the limiting value of $D/8 = 1.0$ m for the 8 m diameter well, indicating adequate safety with no tensile stress developing at the well base under any construction load combination.
- The use of the STAAD.Pro software, which uses 9 structural members with fixed base condition at the well foundation, turned out to be an effective and reliable approach for analyzing this type of structure during the construction period.

- The diaphragm part of the structure (Member 2 to Member 7) is vital in transferring the unequal cantilever loads to the pier shaft and needs particular attention in this stage of construction.

6.2 Future Scope

The current research can be expanded in the following ways:

- Analysis of dynamic behavior: Well foundation behavior in earthquakes along with unbalanced loads due to construction process.
- Time dependent effect: Effect of creep, shrinkage, and prestress loss on cantilever stiffness and subsequently foundation loading.
- Soil-structure interaction: Modification of fixed base by introducing soil springs (Winkler Foundation).
- Parametric study: Change of well diameter, pier height, and segment weights to create design charts for critical eccentricity and FOS.
- 3D analysis using solid element: Modeling well foundation as solid or shell elements using software like STAAD.Pro/Ansys to consider the well steining and curb stresses.
- Construction phase loadings: Monitoring and recording well foundation performance at real-time while constructing cantilever.

Stability Analysis of Well Foundation During Cantilever Construction of segmental PSC Box Girder Bridge

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