

**FINITE ELEMENT MODELLING OF UNDERGROUND TANKS**ANEKHA SUNIL<sup>1</sup>, ANUSUDHA VISVANATHAN<sup>2</sup><sup>1</sup>PG Scholar, Department of Civil Engineering, JAIN (Deemed-to-be University), Bengaluru- 562112, Karnataka, India<sup>2</sup>Assistant Professor, Department of Civil Engineering, JAIN (Deemed-to-be University), Bengaluru- 562112, Karnataka, India

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**ABSTRACT**

All know that water is the most vital requirement of human beings for better livelihood. As the population is growing day by day in our country with rapid speed it is the need of time to study storage capacity and shapes of storage tanks. These tanks are very useful in such areas where rivers do not flow for the whole year and water available only during monsoon season through rainfall. Underground concrete tanks are durable, underground structures used for storing water or sewage, offering benefits like saving above-ground space and protecting contents from contamination. Underground tanks are generally made up of Reinforced Cement Concrete (RCC) and are used in residential, commercial, and industrial spaces for applications like water storage, irrigation supply, and sewerage systems. Main considerations for such tanks are adequate waterproofing and structural integrity preventing leakage and deterioration over a period of time. Finite element modelling (FEM) is an efficient method for analysing how such underground tanks behave under different ground conditions. This methodology allows to estimate and predict how the soil/ rock behaves with the concrete structure, how the internal stresses in the tank change at the time of excavation, and how the support systems behave. By creating a numerical model of the underground environment, FEM helps calculate deformations in the tank, identify potential stability problems like uplift, and improve the design and safety of underground projects. This study provides a basic overview of how FEM is can be used for analysis of underground tanks and highlights its advantages and common challenges in practical applications.

*Keywords: underground tank, finite element analysis, STAAD Pro., Hydrostatic pressure, Earth pressure, reinforced concrete, soil-structure interaction*

**INTRODUCTION**

Underground tanks are commonly used in our water supply systems, wastewater management, industries, fire-fighting needs, irrigation facilities, and environmental protection facilities. These tanks are typically constructed using reinforced concrete due to its durability, impermeability, and strength under compressive forces. An underground tank functions as a buried structure, interacting at the same time with the external soil, groundwater, and internal stored liquid. This simultaneous interaction with multiple forces makes the behaviour of underground tanks significantly more complex than that of above-ground tanks. These tanks a more durable long-term liquid storage option which have been widely used nowadays in urban infrastructure. Due to their underground placement, they are also protected from UV rays, extreme weather, vandalism and fire as well. These concrete tanks can be Cast-in-Situ or precast and offer a design life of around 20 to 50 years depending on the maintenance given to the tanks. Proper waterproofing ensures increased longevity of these tanks. When compared to overhead tanks, underground tanks have additional forces like lateral earth pressure from outside, surcharge loads, external hydrostatic pressure from groundwater, uplift forces due to the ground water, and temperature-induced stresses. These forces act simultaneously and often non-linearly, making manual design methods insufficient and complicated to capture the realistic structural response. Therefore, using Finite Element Analysis (FEA) becomes essential to accurately model and evaluate the performance of underground tanks. FEM enable engineers to understand the stress distribution, bending moments, shear forces, crack behaviour, soil-structure interaction (SSI), and displacement profiles with better precision. Modern structural software such as STAAD.Pro, ANSYS, or ABAQUS can simulate realistic boundary conditions, material behaviour, and complex loading patterns, making FEM a preferred analysis method for advanced research and design.

**Importance of Underground Tanks.** The usage of underground storage tanks is enhancing due to the limited availability of land and space in urban infrastructure, requirement for a concealed storage for aesthetic and safety reasons, protection from environmental factors like sunlight, wind, or temperature variation, space optimisation in high-density urban areas and for efficient water resource management. Underground tanks need to be structurally sound to ensure watertightness and stability under both empty and filled conditions. The tank empty condition is often most critical because the water pressure which stabilises the walls internally from the external earth pressure is absent, leading to greater net inward pressures from the surrounding soil around the tank.

**Challenges in Designing Underground Tanks.** Designing underground reinforced concrete tanks involves several complexities: Soil Pressure and Surcharge Effects, Water Pressure and Uplift Forces, Structural Discontinuity Stresses, Serviceability Requirements, Soil-Structure Interaction (SSI).

**Analytical design methods** assume simplified earth pressure diagrams and ignore SSI, whereas FEM allows realistic modelling of the same. Traditional methods of analysis, though reliable, often make simplifying assumptions that may not accurately capture the true three-dimensional behavior of tanks under the effect of combined loads. With advancements in computational structural analysis, software such as STAAD.Pro. provides an effective platform to perform finite element modeling (FEM) for accurate simulation of stress, deformations, and failure mechanisms.

**Moody Chart for rectangular Walls and slabs:** It is an essential tool used in structural engineering for the analysis and design of two-way reinforced concrete slabs. It offers a graphical solution to determine moment coefficients for slabs with various support conditions, such as simply supported, fixed, or a combination of both. These charts were developed by Prof. H.C. Moody and are widely referenced in slab design procedures, especially under uniformly distributed loads. Moody's Chart is a graphical representation that provides moment distribution coefficients for slabs based on: Aspect ratio (a/b) – the ratio of shorter to longer span of the slab, Support condition – whether edges are fixed, simply supported, or continuous It simplifies the manual calculation of bending moments (Mx and My) in both directions of a slab panel, making the design process quicker and accurate

**Need for Finite Element Analysis.** Finite element modeling (FEM) of underground structures is a computational technique that discretizes the structure into smaller elements to analyze their behavior under various loads and conditions. This method is used to simulate stress and strain, predict performance, and assess safety for complex underground projects like tunnels, stations, and caverns. Key steps include discretizing the geometry, defining soil and structural properties, applying boundary conditions, and solving for unknowns to interpret the results. Detailed Stress Interpretation, Realistic Load Simulation, Accurate Soil-Structure Interaction, Evaluation of Serviceability Performance, Optimisation of Structural Elements.

**STAAD Pro Software for FEM.** STAAD.Pro software is a very widely used structural analysis and design software in civil engineering for modeling, analyzing, and designing structures like buildings, bridges, tanks etc. It allows engineers to apply various loads, such as wind, soil pressure, internal water pressure and seismic forces, and perform comprehensive analyses to ensure the safety and stability of structures according to international design codes. STAAD.Pro provides a flexible modeling environment, fluent data collaboration, and advanced features.

**MODELING AND ANALYSIS**

The underground tank is modelled using plate elements for walls and slabs, and beam elements for edge stiffeners if required. The Finite element modelling captures the behaviour of the structure under soil pressure, water pressure, surcharge loads, and uplift effects. Geometry of the Tank: A rectangular reinforced concrete tank considered with the following dimensions: Internal Length (L): 27.5 m, Internal Width (B): 7.0 m, Internal Height (H): 7.0 m Wall Thickness: 750 mm and base Slab Thickness: 700 mm assumed, Depth of tank for initial calculation is taken at 6.5m below Ground level. SBC is assumed 15T/m<sup>2</sup>

Material Properties: Material properties are defined as per IS 456:2000 and IS 3370 (Part 1):2021.

Grade of Concrete considered is M30 since it's a liquid retaining structure; Unit Weight: 25 kN/m<sup>3</sup>, Modulus of Elasticity (E):  $E = 5000 \sqrt{f_{ck}} = 5000 \sqrt{30} = 27.38 \text{ GPa}$ , Poisson's Ratio: 0.17, Modulus of Rupture: 3.2 MPa, Clear cover of 50mm adopted for the tank walls and base slab based on the exposure condition specified in IS code. Water: Unit Weight: 9.81 kN/m<sup>3</sup> (rounded off to 10 kN/m<sup>3</sup>). Soil Backfill: Unit Weight of soil (dry state): 20 kN/m<sup>3</sup>, Unit weight of soil under submerged condition: 10 kN/m<sup>3</sup>, Angle of Internal Friction ( $\phi$ ): 30°, Coefficient of Active Earth Pressure:  $K_a = \frac{1 - \sin \phi}{1 + \sin \phi} = 0.33$ .

**Finite Element Modelling in STAAD.Pro.** Element Types: Plate Elements (4-noded): Quadrilateral meshing is used for Tank walls, Base slab and walkways. These elements can resist in-plane and out-of-plane loads (bending + shear + membrane action). Beam Elements: it is used for Edge beams, Wall-slab intersections, if required for stiffness enhancement. Modelling Procedure: First step is to create nodal grid based on geometry. Next is to Extrude walls using plates. After that create bottom slab using plates. Next step is to assign material properties and assign plate thickness. Then Check element connectivity ensuring zero gaps and ensure proper orientation of local axes. Mesh Density: Uniform mesh size of 0.5 m × 0.5 m is adopted. Fine mesh is necessary at Corners, Wall-slab junctions and

Regions expected to have high stress concentrations. Mesh Quality Checks: The aspect ratio shall be close to 1. There shall be no warped or distorted elements and also there should be proper continuity at joints.

Boundary Conditions: Correct boundary conditions are critical for reliable analysis. Base slab nodes are fixed to simulate support from soil or PCC bedding. Walls are modelled monolithically with the base slab by sharing common nodes. For underground tanks, external soil pressure replaces soil springs, unless detailed SSI springs are used. To simulate realistic behaviour:

Base Slab Supports

Plate mat support is given as the support condition which is defined using the subgrade modulus calculated as  $\text{Subgrade Modulus} = \frac{\text{SBC of soil}}{\text{allowable settlement}}$  where Safe bearing Capacity (SBC) of soil is assumed as 15 T/m<sup>2</sup> at the founding depth of and allowable settlement for raft foundation is considered as 40mm in medium soil, 25mm in hard soil and 75mm in very soft soil.

Hence Subgrade Modulus applied to the base plates = 3750kN/m<sup>3</sup> in medium soil, 6000kN/m<sup>3</sup> in hard soil and 2000kN/m<sup>3</sup> in very soft soil. Attached below are the screenshots from the STAAD software platform.

Loading Conditions

The design of reinforced concrete underground tanks requires careful consideration of a variety of loads to ensure structural safety, serviceability, and long-term durability. Underground tanks will be subjected to combinations of water pressure, soil pressure, surcharge loads, uplift forces, seismic hydrodynamic forces, and self-weight, each influencing wall bending, slab deflection, and overall stability. The following subsections describe all relevant loads considered. The tank will be subjected to various loads as per IS 3370 and IS 875. Loads applied include:

Dead Load including Self-weight of all the structural components (DL)

The self-weight of the tank walls, base slab, and roof slab (if provided) is computed using the density of reinforced concrete. Density of RCC is 25kN/m<sup>3</sup>. This load contributes to vertical loads which also provides resistance against uplift pressure. Hence the dead load is important in empty tank condition specifically. Self-weight of concrete plates is automatically calculated by STAAD.Pro based on material density.

Internal Hydrostatic Water Pressure (Internal Pressure)

When the tank is full, internal water exerts a **triangular pressure distribution** on the walls and uniform pressure on the base slab: **Pressure at any depth h from the top of the wall is,  $p_w = \gamma_w * h$ ; where,  $\gamma_w$  (unit weight of water) = 10 kN/m<sup>3</sup>; h = 7m. Therefore,  $p_w = 0$  kN/m<sup>2</sup> at the top of wall uniformly tapering to 70 kN/m<sup>2</sup> at the bottom of the wall.** The maximum pressure is at the base, and it acts **perpendicular** to walls. When the external soil load is acting, this force reduces wall bending by counteracting external soil pressure. Also, the internal water load acts as downward load on the base. Hydrostatic pressure is a primary design load and governs the **full tank** case.

Earth Pressure (External Soil Pressure)

Soil surrounding the tank imposes lateral earth pressure on walls. This is the most critical loading condition because water is absent on the inner face. Lateral earth pressure is calculated using Rankine/ Coulomb theory where the pressure at any depth h from ground level is given as  $p_s = K_a \cdot \gamma \cdot h$ ; where  $K_a$  is the Coefficient of active pressure:  $K_a = \frac{1 - \sin \phi}{1 + \sin \phi}$ ,  $\gamma$  = unit weight of soil,  $\phi$  = angle of internal friction. Assuming 6.5m of soil height, lateral earth pressure at bottom of wall  $p_s = 0.33 * 20 * 6.5 = 43$  kN/m<sup>2</sup>

Surcharge Load: Surcharge loads arise from adjacent buildings, Vehicular movement near the tanks, stored materials above soil and (or) backfilling compaction loads. These impose additional horizontal earth pressure given as  $p_{\text{surcharge}} = K * q$ ; where q = surcharge intensity, K= earth pressure coefficient. Surcharge increases bending moment in walls and shear in joints. Its taken as 10kN/m<sup>2</sup> here as a thumb rule and this value is on a conservative side. Surcharge load is added along with the earth pressure and applied on the tank

Groundwater Uplift Pressure

For tanks located below groundwater level, upward hydrostatic pressure acts on the base slab.

$p_{\text{uplift}} = \gamma_w * h_{\text{gw}}$ ; where  $\gamma_w$  = density of water = 10 kN/m<sup>3</sup>,  $h_{\text{gw}}$  = height of groundwater above bottom slab taken same as soil height = 7.2m at bottom of foundation.

So

$p_{\text{uplift}} = 72$  kN/m<sup>2</sup> when tank is fully below FGL.

$p_{\text{uplift}} = 51$  kN/m<sup>2</sup> when tank is 2/3<sup>rd</sup> of its height below FGL.

$p_{\text{uplift}} = 29.2$  kN/m<sup>2</sup> when tank is 1/3<sup>rd</sup> of its height below FGL.

Uplift pressure can lead to bottom slab getting uplifted and hence requires additional slab thickness or anchor blocks to balance the net downward dead load of the tank against upward uplift pressure. The weight of soil fill above the roof slab and on top of the raft projections helps to counteract uplift along with the dead weight of the tank. This loading shall be checked under empty tank condition since that is most critical case.

Seismic Loads (Hydrodynamic Pressure)

(As per IS 1893 (Part 2):2014 & IS 3370)

During an earthquake, liquid inside the tank exerts additional seismic-induced pressure known as hydrodynamic pressure. Hydrodynamic effects are divided into:

- Impulsive Component: which is caused by the part of liquid moves which with the wall; This pressure acts like added mass and represents lower mode response.
- Convective Component (Sloshing): which is due to the Free-surface oscillation of the liquid inside the tank. It acts at higher modes and causes pressure peaks near top levels.

Total hydrodynamic pressure = hydrostatic + hydrodynamic (impulsive + convective)

General form:

- $p_i = C_i \cdot \gamma_w \cdot h_p$  (impulsive)
- $p_c = C_c \cdot \gamma_w \cdot h_p$  (convective)

Where:  $C_i, C_c$  = seismic coefficients from IS 1893 tank spectra, h = fluid height. Hydrodynamic force generates additional horizontal force on walls, amplifies bending moments in upper wall region and induces sloshing force on roof slab (if covered). Hydrodynamic load becomes significant in large tanks, Seismic Zone III, IV, V, Tall/narrow tanks.

Load Combinations: As per IS 3370 & IS 456: the following are the combinations adopted.

**Serviceability Combinations**

- Self-weight + Earth Pressure + Groundwater
- Full Water Pressure + Self-weight
- Empty Tank + External Soil Pressure + Uplift
- Earthquake Load + Hydrodynamic Load
- Surcharge + Earth Pressure

**Ultimate Load Combinations**

- 1.5(Dead load + Live load)
- 1.5(Dead Load + External Soil& Pore water pressure + Internal Water Pressure)
- 1.2(Dead Load + External Soil& Pore water pressure + Internal Water Pressure ± Earth Quake load/Hydrodynamic load)

**Case 1: Empty Tank:** Soil pressure (external) + Surcharge+ Uplift pressure + Self-weight

**Case 2: Full Tank:** Internal water pressure + Soil pressure + Reduced uplift + Self-weight

**Case 3: Extreme Condition:** Surcharge + maximum earth pressure + uplift (safety check)

**Case 4: Serviceability condition:** Internal water pressure + Self-weight

OUTCOMES & FUTURE SCOPE

Extraction of Results from STAAD Pro Output

Validation of results from STAAD Procedure

Analytical Method Comparison using the following parameters:

Comparison of STAAD output with Moodys charts

MOODY'S CHART: Moody's Chart is a graphical design tool used in reinforced concrete (RCC) design to analyze and design rectangular sections subjected to combined axial load and bending moment. It provides a quick and rational method to determine the required reinforcement ratio or to check the capacity of a section under compression with uniaxial bending, typically applied to columns and walls.

The Moodys chart used here are as follows:

Case 1: For full height of tank Buried below finished ground level

For wall Long Walls	a	6.875	m		
	b	7	m		
	a/b	0.98214			
For rectangular loading due to surcharge	p =	10	kN/m <sup>2</sup> /m		
Coefficients from chart					
for Mx	0.2613	=====>	Mx =	121.64	kN-m/m
for My	0.2043		My =	95.10	kN-m/m
for Rx	1.2115		Rx =	80.56	kN/m
for Ry	0.845		Ry =	56.19	kN/m
For triangular loading due to external earth pressure	p =	107.5	kN/m <sup>2</sup> /m		
Coefficients from chart					
for Mx	0.0644	=====>	Mx =	322.27	kN-m/m
for My	0.0845		My =	422.85	kN-m/m
for Rx	0.2565		Rx =	183.37	kN/m
for Ry	0.4584		Ry =	327.70	kN/m
Total Design moment					
			Mx =	665.8512	kN-m/m
			My =	776.9253	kN-m/m
			Rx =	395.8953	kN/m
			Ry =	575.8368	kN/m

Comparison Table:

	STAAD	Moodys chart
Mx (kNm/m)	608.38	665.85
My (kNm/m)	534.23	776.93

Case 2: For 2/3<sup>rd</sup> height Buried below finished ground level

For Long Walls	a	6.875	m		
	b	7	m		
	a/b	0.982143			
For rectangular loading due to surcharge	p =	10	kN/m <sup>2</sup> /m		
Coefficients from chart					
for Mx	0.0757	=====>	Mx =	37.09	kN-m/m
for My	0.1184		My =	58.02	kN-m/m
for Rx	0.4093		Rx =	28.65	kN/m
for Ry	0.6149		Ry =	43.04	kN/m
For triangular loading due to external earth pressure	p =	65	kN/m <sup>2</sup> /m		
Coefficients from chart					
for Mx	0.0208	=====>	Mx =	66.25	kN-m/m
for My	0.0461		My =	146.83	kN-m/m
for Rx	0.157		Rx =	71.44	kN/m
for Ry	0.3202		Ry =	145.69	kN/m
Total moment					
			Mx =	155.0115	kN-m/m
			My =	307.2668	kN-m/m
			Rx =	150.129	kN/m
			Ry =	283.101	kN/m

Comparison Table:

	STAAD	Moodys chart
Mx (kNm/m)	155.68	155.01
My (kNm/m)	205.11	307.27

Case 3: For 1/3<sup>rd</sup> height Buried below finished ground level

For Long Walls	a	6.875	m		
	b	7	m		
	a/b	0.982143			
For rectangular loading due to surcharge	p =	10	kN/m <sup>2</sup> /m		
Coefficients from chart					
for Mx	0.0136	=====>	Mx =	6.66	kN-m/m
for My	0.0399		My =	19.55	kN-m/m
for Rx	0.1696		Rx =	11.87	kN/m
for Ry	0.3267		Ry =	22.87	kN/m
For triangular loading due to external earth pressure	p =	32.5	kN/m <sup>2</sup> /m		
Coefficients from chart					
for Mx	0.0039	=====>	Mx =	6.21	kN-m/m
for My	0.0144		My =	22.93	kN-m/m
for Rx	0.0726		Rx =	16.52	kN/m
for Ry	0.1651		Ry =	37.56	kN/m
Total moment					
			Mx =	19.31213	kN-m/m
			My =	63.7245	kN-m/m
			Rx =	42.58275	kN/m
			Ry =	90.64388	kN/m

Comparison Table:

	STAAD	Moodys chart
Mx (kNm/m)	26.47	19.31
My (kNm/m)	74.70	63.72

Conclusion: From the above three cases it can be concluded that FEM analysis is the most optimised method for analysing any structure. Moodys chart results are showing values are on the higher side, hence for fast checking of forces and moments it can be beneficial.

Comparison of stresses in walls and raft for different soil types

Three soil types are compared here: medium soil type, very soft soil and hard soil.

Conclusion: The stresses and displacements are maximum in soft soil and least in Hard soil due to its increased settlement and less support in soft soil.

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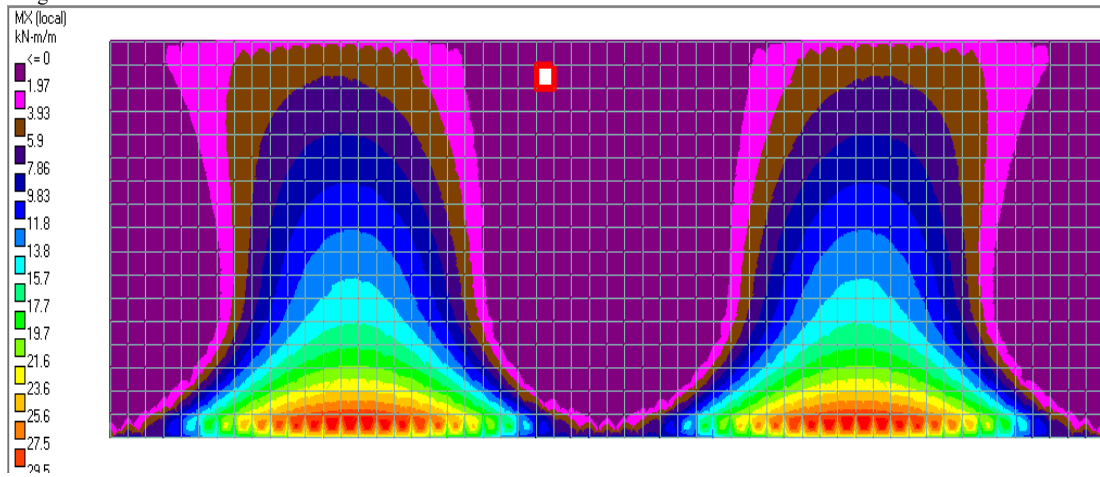


Figure 1 - Mx stress distribution for Long Wall

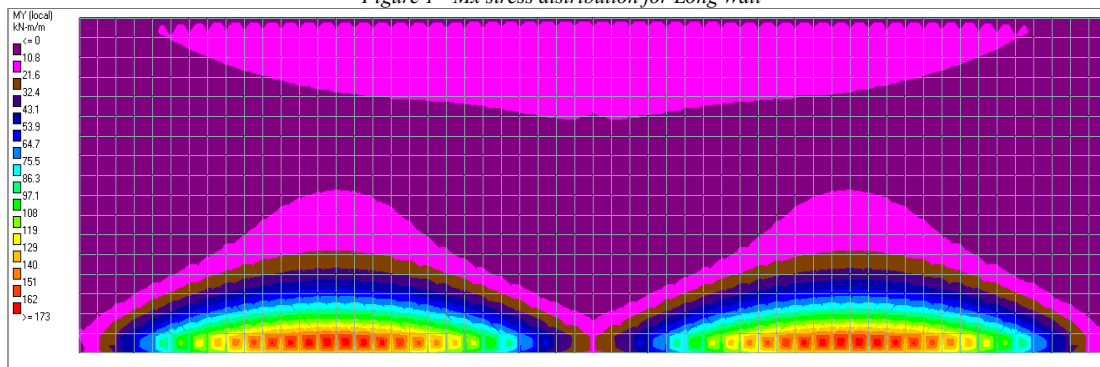


Figure 2- My stress distribution for Long Wall

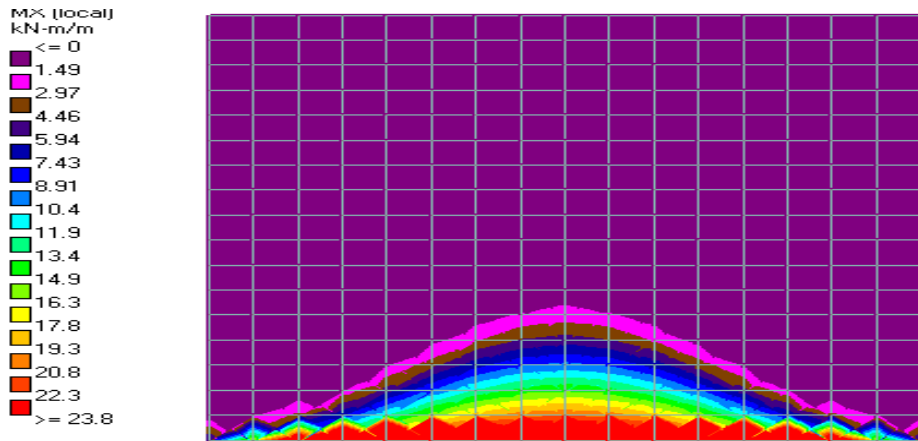


Figure 3 - Mx stress distribution for Short Wall

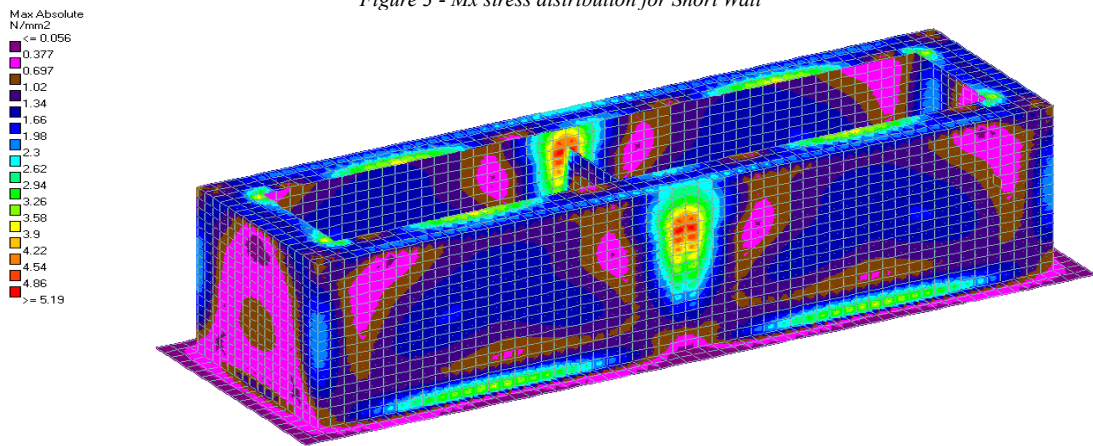


Figure 4 - Max Stress contour for Full tank in Hard soil

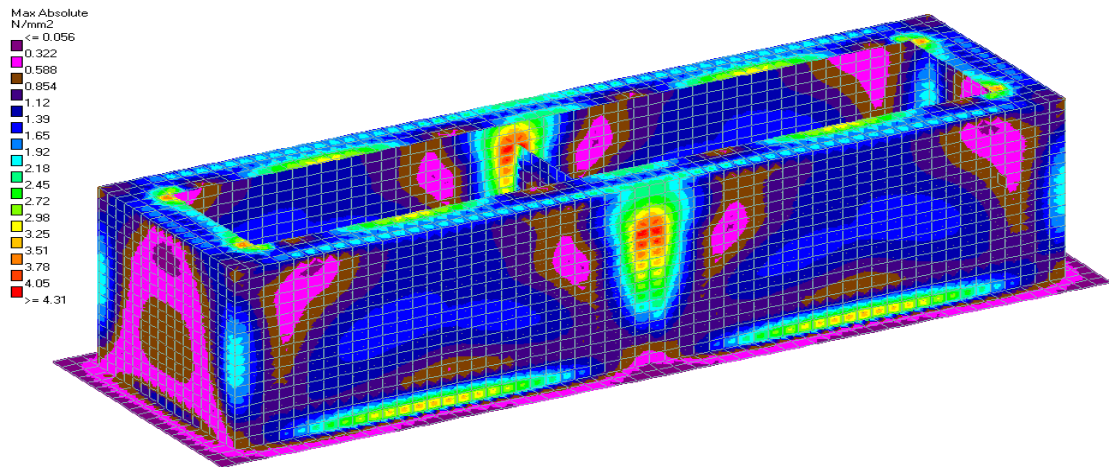


Figure 5 - Max Stress contour for Full tank in Medium soil

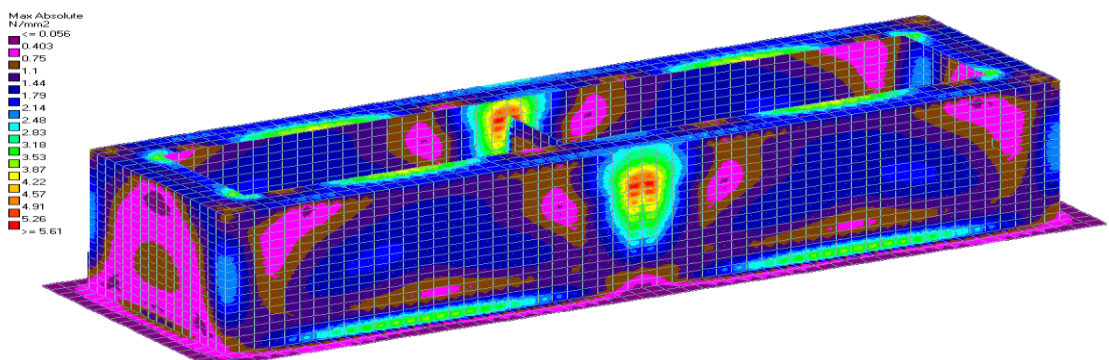


Figure.6 - Max Stress contour for Full tank in Very soft soil