Sustainable Structure and Materials, *Vol. 4, No .1, (2021) 01-11*
DOI: https://doi.org/10.26392/SSM.2021.04.01.001

Challenging Investigations into Structural Design of Lean Oil Unit Used in Refineries

Osama Bedair[*1]

Senior Consultant, 249 Craig Henry Drive, Ottawa, Ontario, Canada
*Corresponding author/ E-mail: obedair@gmail.com

ABSTRACT. *This work describes a challenging structural investigation that was conducted for Lean Oil Unit (LOU) commonly designed in oil refineries. Little guidelines are available in design codes and industrial specifications for design of this type of structures. The paper also describes Numerical models developed to idealize load transfer between various structural systems. Concrete piles are used to support major structures used in the unit. Spring elements are used to simulate soil interaction. Economical strategies and design recommendations are discussed that can be used by practitioners for design of industrial structures and optimize overall project capital cost. The scope of the paper is only limited to the structural design aspects. Chemical or mechanical aspects are not within the scope of the paper.*

Keywords; Structural design, Lean oil unit, Gas processing, steel modules, refineries.

1. INTRODUCTION

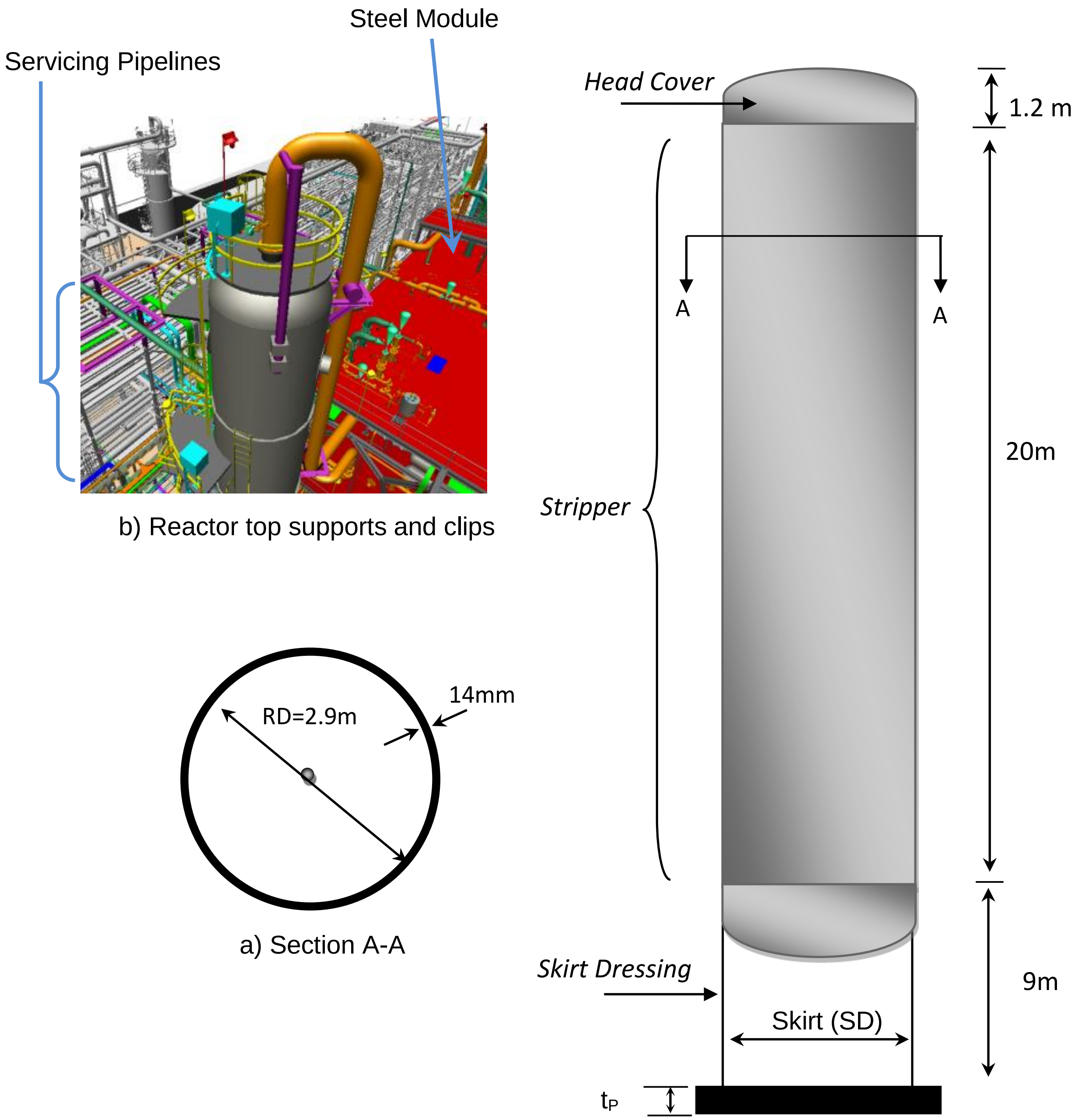
The primary function of lean oil unit (LOU) is to remove gas components in the refining process. This unit is extensively used in hydrocarbon extractions and gas recovery process. The most common application of lean oil absorption system is dedicated to the separation of methane and ethane from the natural gas. Figure 1 shows typical lean oil unit used at refineries. The unit consists of cylindrical reactor and multilevel steel structure. The function of the reactor is primarily to capture and separate as much of ethane as possible. Lean oil enters the top of the reactor and travels downward from tray to tray. The composition of inlet gas contains both methane and ethane which is separated from the gas stream at this process. Service platforms are connected to the reactor at various elevations. Steel ladders are also connected to facilitate access to these service platforms. Steel module (LOSM) is normally provided to support major pipelines and mechanical equipment. The module contains heat exchangers to regulate pipelines temperatures. Steel grating is provided at four levels to service the mechanical equipment.

Limited literature addressed civil engineering aspects in the design of lean oil units. Much of the engineering articles and guidelines focus on the process design aspects. Examples are work published by Froment and Bischoff (1), Levenspiel (2), Fogler (3) and Smith (4). Furthermore, most of the provisions available in current design codes such as AISC (5), AISC (6), ASCE (7), ASCE (8), CSA (9), CSA (10), CSA (11), NRC (12) deal with residential structures. Little attention is given to industrial structures encountered in refineries and gas processing plants. Therefore, it is important to outline structural challenges that are encountered in the design of lean oil units

Published literature addressed structural design issues encountered in heavy industry (13-18). This paper extends the investigations to describe economical strategies for structural design of various systems used in the lean oil units. Finite element strategies are then described to illustrate load transfer mechanisms and soil interactions. Parameters required for foundation and pile support systems are then identified for various loading conditions. The paper also provides recommendations and guidelines to engineers to use in practice.

2. REACTOR SUPPORT SYSTEM

Ethane is extracted from natural gas using lean oil reactors. Lean oil is released to capture the ethane component from the inlet natural gas travelling upward. The product of this process leaves the system as fuel gas. Methane is released out of the reactor and enters gas scrubber. The main components of lean oil reactor are shown in Figure 1. The reactor can be fabricated either as single unit or assembled in pieces on site. The lower cylindrical skirt is used to reduce the heat emission from the reactor. The reactor major components are shown on the left hand side arrows. The right hand side shows the dimension of the case study used in the present investigation. Length of the skirt dressing base is 9m and the vessel head cover is 1.2 m. The length of stripper is variable depending upon the target process capacity.



b) Reactor top supports and clips

a) Section A-A

Figure-1: Lean Oil Tower Components

In this investigation, the stripper length is 20m. Therefore, the total reactor length is 30.2m. Figure 1a shows section A-A through the reactor vessel. Interior pipes might be required depending upon the mechanical design. The reactor internal diameter is (RD)= 2.9m and the shell thickness is 14mm. The cylindrical skirt diameter is (SD)= 3m. The reactor volume is 144.43 m^3 and cross-sectional area is 211 m^2. The reactor is designed for steam out pressure =170 KPa at 135 ˚C. The maximum vessel drop pressure is 20 KPa. Figure 1b shows enlarged detail for external structural supports and clips attached to the reactor.

The stud of this reactor model can be removed towards the vessel without removal of insulation. It is common that shell and the skirt to be painted. The insulation material consists of calcium silicate from skirt fireproofing up to 3m from the ground level. Mineral wool shall be used on the remaining part of the tower. The insulation thickness is 50mm and surface area is 215 m^2. The fireproofing material thickness is 50mm and the surface area is 169 m^2. The reactor weight for various loading conditions is summarized in Table (1). It can be seen that the largest load (231.6 tones) occurs during testing. Weight breakdown of attached accessories is also listed in Table 1.

Table-1: Reactor and external accessories weight summary

Item	**W (tones)**
Reactor (Empty)	38
Reactor (Operation)	112
Reactor (Testing)	231.6
Cable Trays	3.7
External Pipes	12
Insulation	3.2
External clips	1.5
Fireproofing	17

Figure 2 shows a plan of the reactor support structural system. The length of the support base is denoted by (PCL) and the width by (PCW). Octagonal concrete pedestal is projected from the base by distance (D_P). The reactor location is identified by the green circle. The skirt base plate is anchored to octagonal concrete pedestal with geometric parameter (P_1) and (P_2). Note that (P_1) denotes the long side and (P_2) is the short side, as shown by the long-dashed lines in Figure 2.

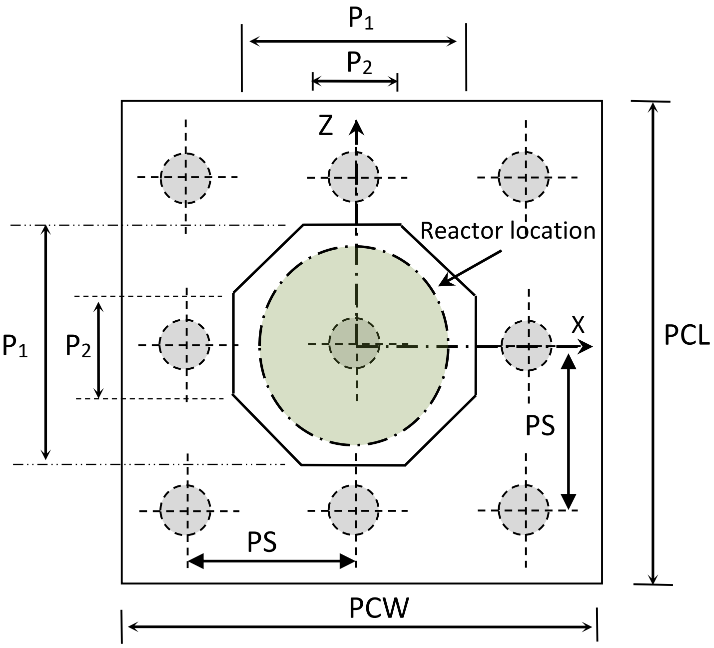


Figure-2: Reactor Support System

In this model, the skirt bottom base plate is anchored to the concrete pedestal using 20 equally spaced anchor rods (5 each quadrant at angular spacing $\theta=18^\circ$). The nominal area of each rode (A_P)= 1,120 mm^2. The exposed anchor bolt length 474mm and the yield strength is $(\sigma_y)_B$=400MPa. Anchor rods must be threaded and comply with the requirements of ASTM A36, A307. Corrosion allowances were considered in the reactor design and anchor rods due to the aggressive climate environment. The reactor support was designed to accommodate operating, testing and erection loading conditions. Design parameters for support design were based on vendor mechanical data sheets.

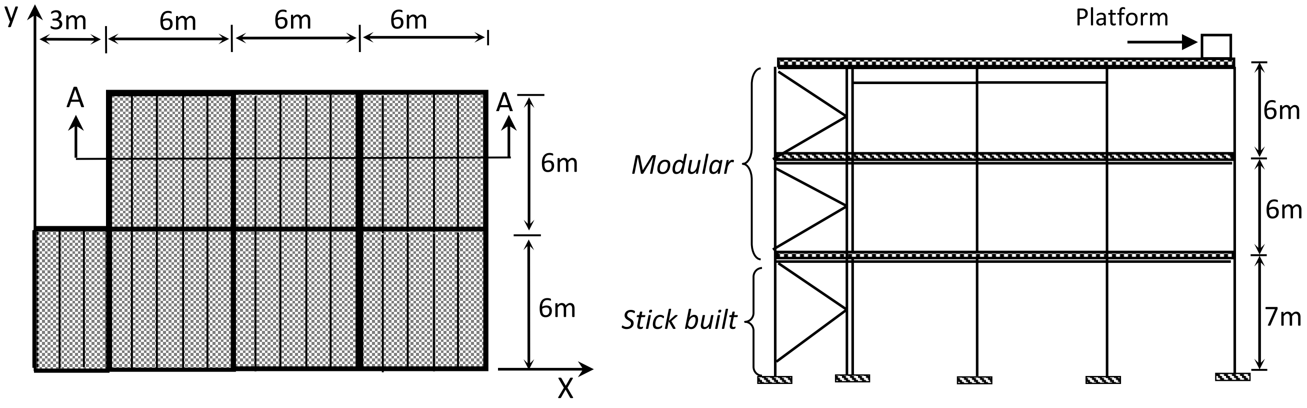
3. ANALYSIS

Numerical models were developed by the author were used to analyze the reactor for various loading conditions and evaluate load transfer to connected structures. The idealized vessel diameter was magnified in the wind analysis to compensate for attached steel platforms and connected pipes. The skirt reactions were transferred to the piles using multiple point constraints. Master nodes were generated at the bottom of skirt elevation. Slave nodes are generated at the anchor bolt locations. Compatibility constraints are enforced along the master/slave nodes to match the six degrees of freedoms (DOF). A second (FE) model was developed using flexural beam elements to transfer the loads from the skirt to the pile cap. Flexural beams are used to transfer the skirt reaction to the pile cap. Load transfer from the anchor bolts was modelled using the procedure developed by Bedair (18). Auxiliary/fictitious nodes at bolt locations were used to transfer the reactor loads into the pile cap. Nodes around bolts were connected to its adjacent node on the pile cap support using extensional and rotational spring elements. Compatibility of displacement in z-direction and rotation in y-direction were imposed in this model.

In the preset model, it is assumed that the pile cap is casted monolithically with the concrete pile. Therefore, the pile head rotations and in-plane translations are fully restrained ($\theta_x=\theta_y=u_x=u_y=0$). The flexural stiffness of the piles was variable to reflect the variation in the formwork casings. Horizontal springs were used to restrain the pile bi-laterally along the embedded length. The sprig stiffness of each soil layer was determined using borehole test data. Flexible supports were used at the bottom of the piles to stimulate the end bearing. Loads were combined according to NBC (12) at service limit state (SLS) and ultimate limit state (ULS) to determine critical loads of concrete support and steel structure. The applied loads are categorized as principal and companion components.

4. Lean Oil Steel Modules (LOSM)

The design of lean oil steel module (LOSM) is placed on the right side of the reactor of Figure 1 and is used to support piping, electrical cable trays, mechanical and electrical equipments. The (LOSM) is supported by piles. Figure 3a shows the plan structural detail of (LOSM). The size of the module is 21m long X 12m wide X 19m tall. The structure consists of four bays in the x direction and two bents in the y direction.



a) Plan

b) Section A-A

Figure 3: Plan Layout of the (LOSM)

Section A-A through the module length is shown in Figure 3b. The top part of the structure consists of two modularized units, each with size (18mx6mx6m). The height of the stick built part is 7m. Pipeline dead load was converted to equivalent uniform distribution of 2.0 KPa per bent. Cable trays dead was assumed as 1.5 KPa for single level trays and 3.0 KPa for double level trays. Fireproofing (type BFP) is used up to 3m from ground elevation. The fire proofing material density is 25 KN/m^3. Grating weight used = 0.5 KN/m^2. The load was approximated using linear load distribution along the runs. Live load is (4.8 kPa) that included temporary/maintenance loads, such as personnel, miscellaneous tools / equipment. Wind load was calculated using NBC (12). Snow was calculated as (1.46 kN/m^2) NBC (12). Earthquake load was calculated using NBC [2010]. Notional load was added to the sway effects for all load combinations. The translational load effect produced by notional lateral loads at each level was approximated by using 0.005 times factored gravity loads contributed by that storey.

5. RESULTS

Lean oil reactor (LOR) was analyzed to compute the reaction forces required to design the concrete support system. Figure 4 shows the bending moment (M) distribution along the reactor length due to wind load. The solid curve represents the empty loading condition case (A) and the dashed curve represents the operational loading condition case (B). It can be observed that a gradual increase in (M) values occurs between the two loading conditions. For example, the mid-height (z)=15m, the bending moment for case (A) is (M)= 730 KN-m and for the operational condition case (B) is (M) =1,050 KN-m. The difference between the two cases is approximately 30%. The base moment for case (A) is (M) =2,665 KN-m and for case (B) is (M)= 3,305.2 KN-m. By similar analogy, the reactor shear forces was computed for case (A) as (Q)=157.6KN and for Case (B) is (Q_R)=194.7 57.6 KN. The difference is 24%.

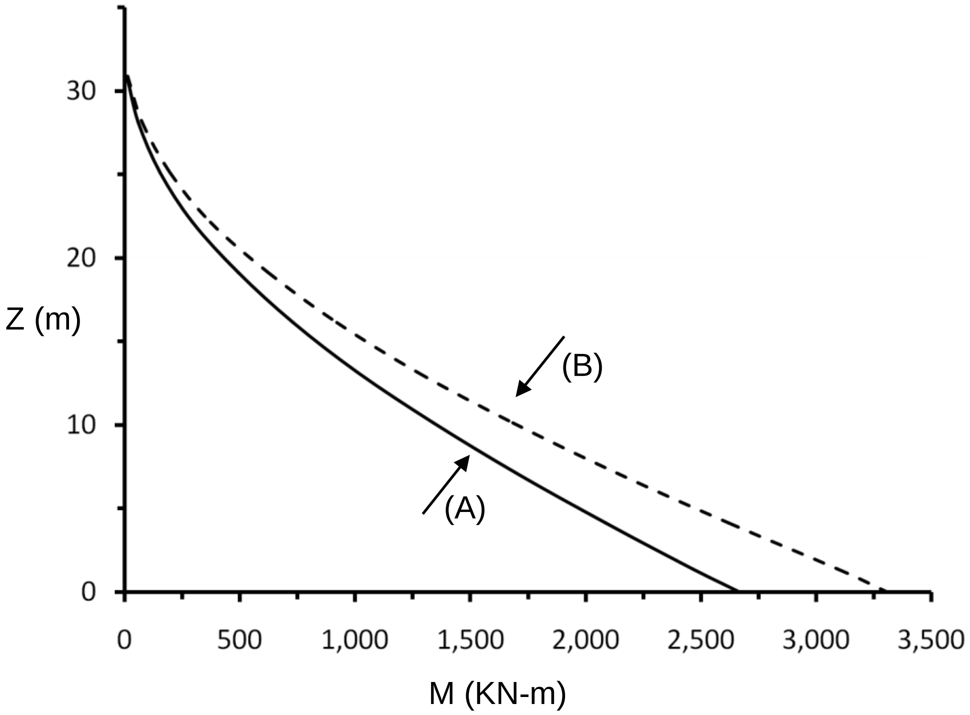


Figure-4: Reactor bending moment distribution

Figure 5 shows the variation of the pile axial capacity (PAC) with embedded length (PEL). The pile diameter used in the analysis is (Φ_P)=750mm. The pile embedded length (PEL) varies between 8m-21m. The initial ground level in the lean oil unit was characterized by gentle slope. Site grading was performed by placement of fill to construction grade elevations up to 4m. The soil layers in lean oil unit (LOU) is illustrated in Figure 5, Layer #1 represents the fill material and consists of fine to medium grained sand. The average thickness of this layer is approximately 5m. Layer #2 consists of fine sand, poorly graded with pockets of clay.

The thickness of this layer is variable over with averaged 4.5 m. Layer #3 is composed of clay till (or occasionally lacustrine clay). This layer is made of silty clay with traces of coarse sand, medium to high plastic, generally stiff to very stiff; average thickness of this layer is 6m. Layer # 4 consists of clay shale (or clearwater formation). The composition of this layer is made up of silty clay with some sand pockets, high plastic, very stiff to hard, with siltstone/claystone levels and occasional nodules. The average thickness this layer is 5 m. Oil sand is made up made up of silty sand inter-bedded with occasional clay lenses at the top, very dense to hard with cemented siltstone levels, oil content is from moderate to rich. The elevation of this layer is variable within the site. The soil bed (denoted as layer #5) is very stiff to hard and can be considered as the bearing layers for pile foundations. Note that the thickness variation of these layers is importance for foundation design, and their variability over the area is the most important factor influencing the pile depth. It can be seen from Figure 5 that by increasing (PEL) the pile compressive capacity increases. The maximum pile strength is attained at (PEL) ≈ 20m. Little increase in (PAC) values is attained for larger embedment length. Axial pile capacity was verified using pile load test data performed at several site locations in the vicinity of the reactor support system. No soil refusals were encountered during testing.

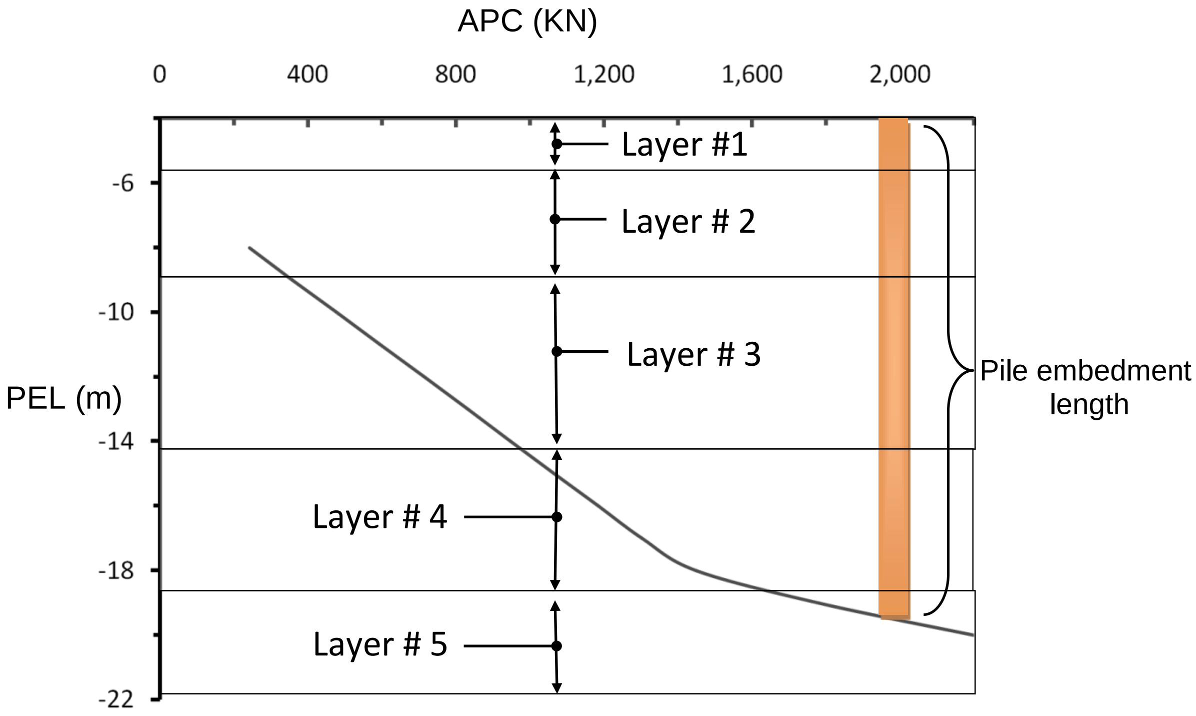


Figure-5: Pile compressive capacity

Pile lateral load capacity (PLC) was reduced to account for the group interaction effect. Figure 6 shows the variation of lateral reduction factor (LRF) with the ratio (PS/PD). The pile spacing is denoted by (PS) and the diameter (PD), as shown in the top sketch. The variation is shown for two pile layouts, assuming equal spacing in the horizontal and vertical directions. The solid curve represents (5x5) pile configuration and the dashed cure represents (3x3) configuration. The variation is shown for (PS/PD) ranging between (2) and (8). It can be seen that as the number of piles increases, the reduction factors (LRF) also increases due to the pile interaction. For example for (PS/PD) = 4, (LRF) increases from 2 to 2.8 by increasing the number of piles from (3x3) to (5x5). It can be noted that the variation becomes steeper for small (PS/PD) ratio.

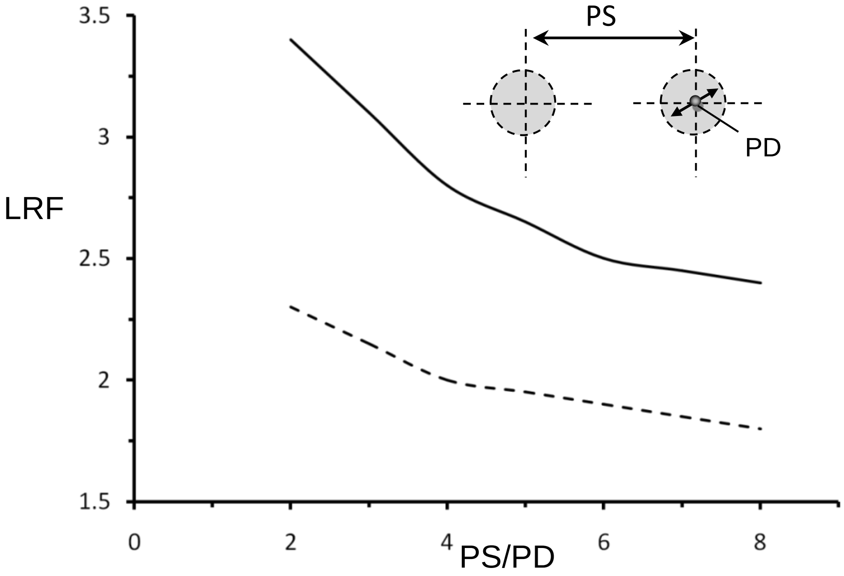


Figure-6: Pile group factors

5.1. Reactor Pile Supports

The maximum (SLS) axial and lateral pile reactions obtained from (FE) analysis were computed as $(PAL)_{SLS}$ =872 KN and $(PLL)_{SLS}$=25 KN. The axial compressive pile capacity using (PEL)=18m is (APC)= 1,500KN. This value can be increased to 2,200 KN by using longer embedment length, i.e. (PEL)=20m. Pile lateral capacity for this condition is computed as (PLC)= 117 KN. Note that the pile group reduction factor was applied. Pile reinforcements were designed using (ULS) pile reactions values. Maximum values obtained using (FE) were computed as $(PAC)_{ULS}$ = 1,142 KN and the horizontal shear $(PLL)_{ULS}$= 35 KN. Based on the study, the author recommends using (3x3) piling configuration for lean oil tower heights less than 64m. Reduced number of piles (3x2) can be used If the soil layer is stronger permits the designer to increase the pile embedment length larger than 20m.

5.2. Recommended Reactor Support Reinforcements

Figure 7 shows the variation of the octagonal pedestal total vertical reinforcements (AS_P) with the geometric parameters $\alpha=(P_1/P_2)$. A key sketch is provided in the figure to identify the required parameters of this curve. A plan and vertical section G-G is shown to identify the reinforcement details. The form of Figure 7 is very useful to utilize in practice to determine the total vertical reinforcements (AS_P) for given (P_1/P_2) ratio. The geometric ratio (α) is ranging between 1 and 4. Note that when (α)=1 the pedestal becomes rectangular shape. The pedestal height used for this curve is (D_P)= 3.8m. It can be observed that by increasing (α), the required vertical reinforcements decrease. For example, the total reinforcement (AS_P) is reduced by 20,000 mm^2 by increasing the parameter (α) from 1 to 5. For large pedestal areas, the author recommends distributing the total reinforcement (AS_P) into multiple octagonal layers. For illustration, assume that (P_1)= 3.5m and (P_2)=1.75m, Therefore, the ratio (α)=2. By using Figure 7, the reinforcement (AS_P)= $53.6x10^3 mm^2$. If the designer is using 35M bar size, then (AS_P)=64-35M. The total vertical reinforcement in this case can be distributed into two octagonal layers, as shown in the key sketch. The designer may also use 40-35M in the outer layer and 24-35M in the smaller layer. Horizontal bars such as 15M@200mm can be used to tie the vertical bars in the octagonal layers.

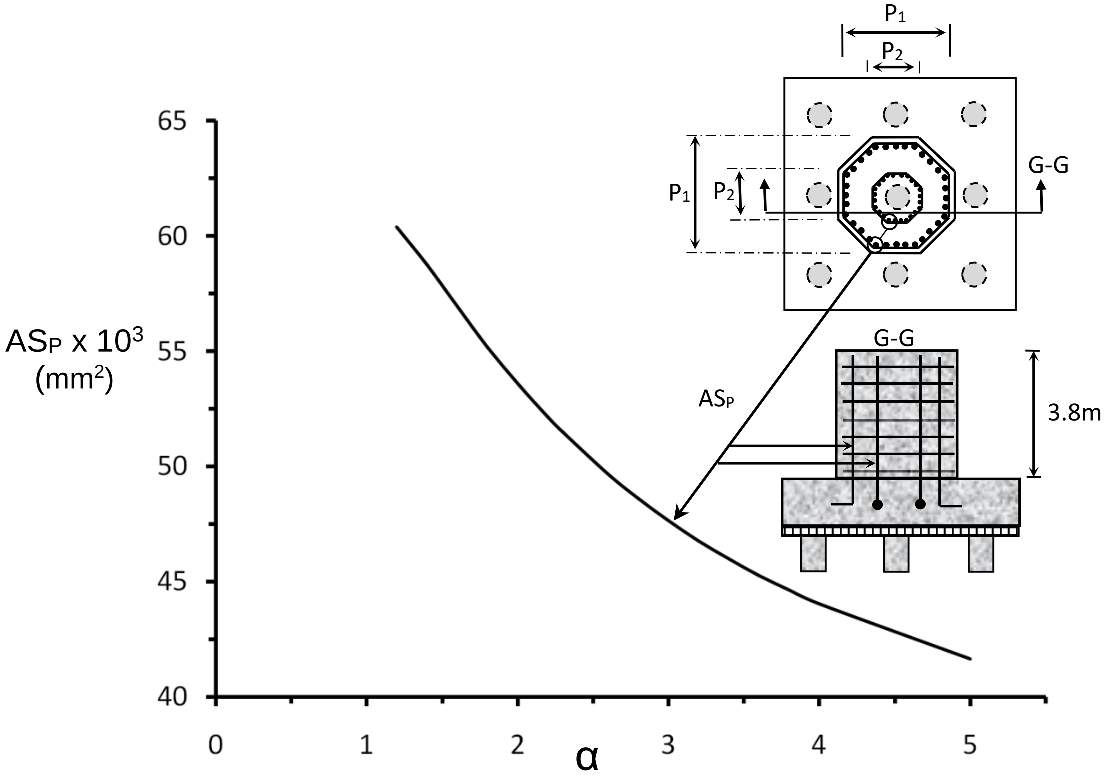


Figure-7: Variation of (AS_P) with (α)

Figure 8 shows variation of the reactor support reinforcements with geometric parameter (β). The parameters required to use the curves are shown in the key sketch. A plan and section GG is provided to show reinforcement layout. To maintain clarity, the pedestal parameters are removed. Figure 8 format is very useful to utilize in practice to determine the pile cap reinforcements (AS_{F1}) and (AS_{F1}) for given (β). The solid curve represents reinforcement (AS_{F1}) and the dashed curve represents (AS_{F2}). The geometric parameter (β) ranges between 6 and 11. Note that in determining (AS_{F1}), the designer should use $(\beta)= (PCL/t_F)$ and to use (PCW/t_F) to determine (AS_{F2}). For constructability and fabrication advantages, the top and bottom (T&B) reinforcements in each direction were assumed to be identical. This assumption leads so significant simplifications in bending bar schedules and reinforcement placements. It can be observed that by increasing (β), the required horizontal reinforcements decrease. For illustration, by increasing (β) from 6 to 11, the longitudinal reinforcement (AS_{F1}) is reduced by 15,000 mm^2 and (AS_{F2}) is reduced by 9,400 mm^2. For deep pile-cap thicknesses $(t_F > 1$ m), the author recommends using additional intermediate layers in both directions.

To provide numerical insight, assume the reactor support size (PCL)=(PCW)= 6.8m and (t_F)=1m. The foundation maximum (FE) moment was computed in this case as (M)=1,500 KN-m. The concrete support was modelled using 1,412 shell elements, a total of 8,472 degrees of freedom (DOF). The concrete design parameters are; (f_y) = 400 MPa; (f_c) = 30 MPa; (d_F)=905mm,(ϕ_s)=0.85, (ϕ_c)=0.6, (α_{F1}) =0.85, (β_{F1})= 0.9, (c/d)=0.64,(K)=0.27. Using Figure 8, the horizontal reinforcement (AS_{F1})=27,200 mm^2 and (AS_{F2})=17,000 mm^2. If the designer decides to use 30M bar size, then the required support reinforcements are (AS_{F1})= 30M @175mm and (AS_{F2})=30M@275mm. The maximum factored shear force $(V_F)_{Max}$=1,142KN. The concrete shear strength (V_S) = 2,760 KN and punching shear resistance (V_{PS}) =3,045 KN > 1,142 KN. The support bearing resistance is (f_b) = 12.4MPa. The maximum pedestal bearing stress was computed as 0.43 MPa.

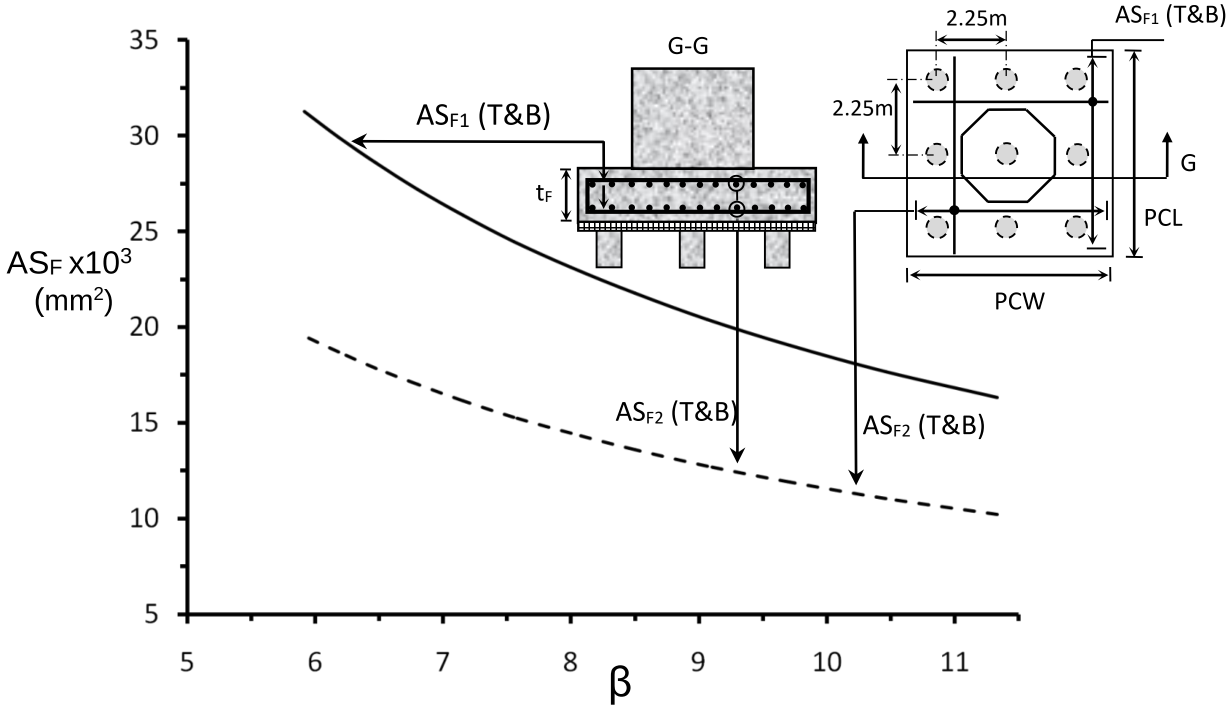


Figure 8: Variation Of (AS_F) with (β)

5.3. Steel Module (LOSM)

The (LOSM) structure was modelled using 507 members with total of 2,260 DOF. The stair case tower was modelled separately for convenience in the numerical simulation. The design is based on mechanical, piping and vendor drawings. Operational load was idealized at five points and is summarized in Table 2. Note that (OP1) is linearly distributed load and (OP2)-(OP5) are point loads.

Table-2: Operational Load Idealization

Load	Magnitude
OP1 (KN/m)	10
OP2 (KN)	10
OP3 (KN)	3
OP4 (KN)	10
OP5 (KN)	3

Thermal loads (TL) arising from contraction or expansion of the members due temperature changes were modelled. The temperature change (ΔT) = ±40°C was used for steel members. Pipe friction force at start-up and shut down conditions was approximated using uniform horizontal loading of (PFF) =1.5 kN/m Pipe anchor force was calculated as (PAF1)= 7.5 KN and (PAF2)= 3 KN.

The maximum beam vertical deflections was computed as (δ_{max}) = 8.5 mm. The allowable beam vertical deflection (δv)=15 mm. The maximum frame sway deflection (δ_H) =57 mm. The allowable sway deflection is

60 mm. A unity check was performed for ultimate limit state loading conditions to confirm compliance with CSA-S16 requirements. The maximum (ULS) unity check=0.67

The maximum (SLS) pile reaction for (LOSM) in for erection loading condition is $(P_{SLS})_{ER}$= 526 KN, $(Q_{SLS})_{ER}$= 68 KN. These values were obtained using load combination (DL+TH+WL+0.5 LL). Note that it is assumed that the pile cap is not cased at this loading condition. Therefore, the pile head is treated as free headed. The lateral pile capacity for this boundary condition is $(Q)_{All}$= 240KN. The maximum (SLS) pile reactions for operating and testing conditions are $(P_{SLS})_{OP/TE}$= 851 KN, $(Q_{SLS})_{OP/TE}$=89KN. Note that for this loading condition the pile forms monolithic connection with the pile cap and the lateral pile capacity must be determined using fixed headed boundary condition. The lateral pile capacity for this case is (PLC) = 323KN. The axial compressive pile capacity in both cases using embedment length (PEL)= 18m is (PAC)= 1,550. KN. Pile reinforcements were designed using (ULS) reactions for operating and testing conditions $(P_{ULS})_{OP/TE}$=1070 KN and $(Q_{ULS})_{OP/TE}$=115 KN.

The maximum bending moment of the pile-caps supporting (LOSM) (M_{max})= 120 KN-m/m By using 15M rebar, it was economical to use identical top and bottom reinforcements each way (AS)=15M@150mm. The concrete shear strength is 1,703 KN. The maximum shear load is 792 KN.

6. CONCLUSIONS

This paper presented structural investigation of lean oil unit (LOU) used in oil refineries. The design of the reactor and (LOSM) were described. Little guidelines are available in practice for design of this type of structures. The paper also described FE models to idealize load transfer from the lean oil reactor to the support system. Circular concrete piles are used to support major structures in the unit. Multiple point constraints were imposed on the rotation/displacements of the attached elements. Spring elements are used to simulate soil interaction. Design recommendations are presented that leads to savings in material cost. The described procedures can be used by practitioners for design of industrial structures to optimize overall project capital cost. Based on this study, the author recommends using magnification factors to the vessel diameter to account for attached platforms and pipelines that are connected to the reactor. Also, the stiffness should be reduced to account for corrosion.

7. REFERENCES

1. Froment, G. F. and Bischoff, K. B. (1990) Chemical Reactor Analysis and Design. John Wiley, USA.
2. Levenspiel, O. (1998), Chemical Reaction Engineering, 3rd Ed., John Wiley and Sons, USA.
3. Fogler, S. (2016), Elements of Chemical Reaction Engineering, 5th Edition, Prentice Hall, USA.
4. Smith, J. M. (1981) Chemical Engineering Kinetics, 3rd Ed., McGraw Hill, USA, USA .
5. AISC (2006) Steel construction manual. 14th ed. Chicago: AISC.
6. AISC (2010) Design of blast resistant buildings in petrochemical facilities: ASCE petrochemical committee, task committee on blast resistant design. New York: ASCE.
7. ASCE (2010) Minimum design loads and other structures. ASCE/SEI 7. Reston, VA: ASCE.
8. ASCE’s Task Committee on Wind-Induced Forces (2011) Wind loads for petrochemical and other industrial facilities. Reston, VA: ASCE.
9. CSA (Canadian Standard Association) (2017) Design and assessment of buildings subjected to blast loads.CSA S850-12. Rexdale, Canada: CSA.
10. CSA (Canadian Standards Association) (2004). Design of concrete structures. CAN/CSA-A23.3-04. Rexdale, Canada: CSA.
11. CSA (Canadian Standards Association) (2007) Limit states design of steel structures. CAN/CSA-S16-01. Rexdale, Canada: CSA.

12. NRC (National Research Council of Canada) (2010) National building code. Ottawa, ON: National Research Council of Canada.
13. Bedair, O. (2020) " Global Dynamic Response of Piperacks and Steel Modules Subject To Accidental Vapor Cloud Blast Explosions” Sustainable Structures and Materials, Vol. 3 (2), 1-12

14. Bedair, O. (2020) Economical Damage Classification Procedure for Blast Resistant Buildings in Petrochemical Plants" ASCE, Practice Periodical on Structural Design and Construction,25(3), 04020020.
15. Bedair, O. (2015) " Design Of Mobile Facilities used In Surface Mining Projects " American Society Of Civil Engineering, Practice Periodical on Structural Design and Construction, Vol 21 (1), 04015007
16. Bedair, O. (2012) "Residual Strength Assessments of Defective Stiffened Plates Used in Marine and Aerospace Structures", Recent Patents on Engineering, Vol. 6 (2), pp. 96-103
17. Bedair, O. (2014) Modern Steel Design and Construction Used In Canada's Oil Sands Industry. Journal of Steel Design Construction and Research", 7 (1), 32-40, DOI:10.1002/stco.201350005
18. Bedair, O. (2011) Cost-Effective Modeling Strategies For Spliced Steel Connections. Journal of Applied Mathematical Modelling, 35 (4), 1881-1892, DOI:10.1016/J.APM.2010.10.017.