Cost Optimization of Offshore Steel Pipe Rack Structure By Modular Design Technique

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Abstract- *Structural steel pipe racks typically support pipes, power cables and instrument cable trays in petrochemical, chemical and power plants. Modular design, or "modularity in design", is a design approach that subdivides a system into smaller parts called modules or skids that can be independently created and then used in different systems. Analysis and design of a modular steel pipe rack is generally done using the concepts provided in PIP STC-01015, NORSOK N-004, API-RP etc. PIP STC-01015 talks about the basic philosophy & types of loadings to be considered in the analysis & design of a structural steel pipe rack. NORSOK N-004 talks about lifting & transportation analysis of steel structures. Structural steel quantity of full pipe rack directly supported on offshore platform shall be compared with the structural steel of the modular pipe racks. Modelling, analysis and design of steel pipe rack shall be done in STAAD.Pro software. Aim here in this study is to reduce the engineering, design, construction & installation cost of structural steel pipe rack after dividing into number of modules.*

Keywords- Steel pipe rack, modular design technique, PIP STC-01015, NORSOK N-004, API-RP, STAAD.Pro

I. INTRODUCTION

Structural steel pipe racks typically support pipes, power cables and instrument cable trays in petrochemical, chemical and power plants. Occasionally, pipe racks may also support mechanical equipment, vessels and valve access platforms. Main pipe racks generally transfer material between equipment and storage or utility areas. Storage racks found in warehouses are not pipe racks, even if they store lengths of pipe. A pipe rack is the main artery of a process unit. Pipe racks carry process and utility piping and may also include instrument and cable trays as well as equipment mounted over all of these. Pipe racks consist of a series of transverse bents that run along the length of the pipe system, spaced at uniform intervals typically around 20 ft. To allow maintenance access under the pipe rack, the transverse bents are typically moment frames. Transverse bents are typically connected with longitudinal struts.

Pipe racks are necessary for arranging the process and service pipelines throughout the plant. A large number of process pipelines, flare lines and manifold lines running through this racks from one equipment to another, or from one unit to another. Also attached is piping, leading to the utility group, such as water, steam, condensate, working air, instrumentation air and nitrogen. Electrical power cables supported by cable ducts are also placed in the pipe rack, but separate from the pipelines.Air-cooled Heat Exchangers are often supported above pipe racks for economy of plot space. A pipe rack is usually constructed of Hot-dip galvanized steel or concrete frames called bents, on top of which the pipeline rests. Pipe racks are typically multi-level. Pipes in a pipe rack are normally at a height where it is possible to walk underneath. They are designed so that the clearance under the rack is sufficiently high that mobile lifting equipment can operate under the rack for maintenance purposes.

Fig.1. Typical Offshore PipeRack

All piping shall be routed so as to provide a simple, neat and economical layout, allowing for easy support and adequate flexibility. Piping should be arranged on horizontal racks at specific elevations. When changing direction (from longitudinal to transverse or vice versa) the piping should change elevation, but care shall be taken to avoid pockets. No piping shall be located inside instrument, electrical or telecommunication control/switchgear rooms, except fire-fighting piping serving these rooms. Rack piping shall be designed with expansion loops capable of handling relative movement of platforms in design storm conditions. Cold and hot piping should be grouped separately with hot, non-insulated, lines at a higher elevation than cold lines. Uninsulated lines with possibility for ice build-up, shall not be run above walk ways. When expansion loops are required, lines should be grouped together and located on the outside of the rack. Small pipes should be grouped together to simplify support design. Locating small pipes between large pipes shall be avoided especially when the large lines are hot. To save space and for economic reasons, clamped pipe supports at an angle of 45 degrees should be used. Heaviest lines should be located furthest from center of the rack. Sloping pipes, such as flare headers and drain lines, should be located together and the routing established at an early stage in the design period to prevent difficulties which may occur if other process and utility lines are routed first. Utility headers for water, steam, air, etc. shall be arranged on the top of multi- tiered pipe racks. All Valves requiring operation during normal or emergency conditions shall be accessible from a deck or platform. Isolation Valves shall preferably be accessible from deck or platform. However, if this is not possible, Valves shall be positioned such that access from temporary facilities is obtained. Fire water ring main isolation Valves shall always be accessible from deck or platform. Pressure relief devices (Relief Valves, rupture discs) shall be accessible and installed for easy removal from deck or permanent platform. Relief Valves shall be installed with the stem in the vertical position. Other Valves may be tilted, as long as the stem is above horizontal position. When ESD Valves are installed as isolation Valves, they shall be located as close as possible to the fire/blast partition.

1.1 Purpose & Need ofWork

The monotonous procedure for construction of steel pipe rack on offshore platform is to transport all the cut-sections to the corresponding site, and then assemble them with welded/bolted connections. Perhaps, while following this procedure there are lot of complications while erecting the structure. We can avoid these complications by adopting modular design technique. In this, we build the whole structure in small modules on onshore site, so that it can be easily transported to offshore site. Then it can be quickly assembled with bolted connections only.

Modular design, or "modularity in design", is a design approach that subdivides a system into smaller parts called modules or skids, that can be independently created and then used in different systems.

II. DESCRIPTION OF STRUCTURE

Analysis and design of a modular steel pipe rack is generally done using the concepts provided in PIP STC01015, NORSOK N-004 etc. PIP STC01015 talks about the basic philosophy & types of loadings to be considered in the analysis & design of a structural steel pipe rack. NORSOK N-004 talks about lifting & transportation analysis of steel structures.

Input from piping discipline is to be considered for a pipe rack design. Piping input shall be in the form of layout drawing & piping loads for a refinery project. Layout drawing will show the location of piping loads & piping load input will give the intensity of loads for big bore pipe lines. For small bore pipe lines, loading shall be considered as per PIPSTC01015.

Modelling of Structural Systems:

A typical pipe rack of length 30 m, width 6 m & height 7.6 m shall be considered for the thesis. Pipe rack shall have 3 tiers. Height of first tier is 3.6 m, second is 5.6 m and third is 7.6 m from bottom.

Pipes shall be supported on each tier except the third one. Electrical cable tray and instrument cable tray shall be supported at top. Modelling, analysis and design shall be done in STAAD.Pro software.

Firstly, the in-place structure (30 x 6 x 7.6) which is to be placed and supported on offshore platform shall be prepared. Then the same module shall be analysed for lifting and transportation forces. Then by considering modular design technique, two different modules of 6m length and 12m length shall be prepared and analysed for lifting and transportation forces.

Basically, following models are to be developed in STAAD.Pro –

Model 1:- Design of Full Pipe rack supported on Offshore Platform
Model 2 :- Design of Modular Pipe rack (6m length)
Model 3 :- Design of Modular Pipe rack (12m length)

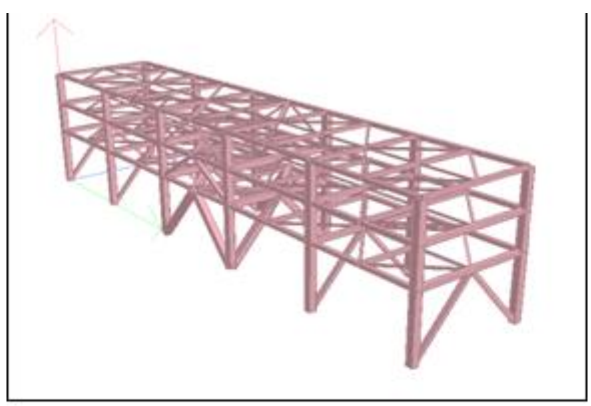

Fig.2. 3D view of full piperack

Pipe rack is designed as moment resisting frames in the transverse direction. The lateral forces in the transverse direction are transferred to base plate/ foundation by moment resisting frame. In the longitudinal direction, there is continuous level of beam struts on each side. Vertical bracing in the longitudinal direction is provided to carry the longitudinal forces, transmitted through the beam struts, to the base plate/ foundation level.

III. DESIGN LOAD CALCULATION

Basic loads are applied in Staad Model, as applicable, on the structure and its elements in form of 19 number of Load Cases and 73 type of load combinations. Load Cases includes all the basic loads such as Dead loads, Live Loads, Wind, Seismic, Test loads, Operating loads, etc. Each load case is described in brief in this section. ASCE705 primary load cases are as follows:

- Longitudinal Earthquake Load –EL
- Transverse Earthquake Load – ET
- Longitudinal Earthquake Load (Pipe Only) – ELP
- Transverse Earthquake Load (Pipe Only) –ET
- Dead Load –DL
- Cable Tray + Cable Load –CTC
- Pipe Empty Load –PE
- Pipe Content Load –PC
- Pipe Test Content Load –PT
- Longitudinal Pipe Friction Load –PFL
- Transverse Pipe Friction Load –PFT
- Longitudinal Pipe Anchor Load –PAL
- Transverse Pipe Anchor Load –PAT
- Pipe Contingency Load On Longitudinal Tie – PCL
- Live Load –LL
- Temperature Rise Load – TR
- Longitudinal Wind Load –WL
- Transverse Wind Load –WT
- Displacement Load

IV. DESIGN PARAMETERS

Design parameters has been applied in STAAD model under two different sections namely: Limit State of Service ability and Limit State of Collapse. All the different load combinations are followed by PIP STC-01015. AISC-ASD has been followed for steel design. Serviceability check is done for all the beam members only to check deflections. Collapse check is done for each structural member of pipe rack to check overall strength of members.

Limit State of Serviceability:

1. Deflection DJ1 & DJ2 to allbeams
2. DFF 400 to allbeams
3. Utility Ratio 0.9 for allbeams

Limit State of Collapse:

1. Yield Strength 235000 kN/m^2
2. BEAM 1 for all
3. NSF 0.7 to all bracing members
4. LX, LY, LZ, UNB &UNT to all beams
5. KY, KZ 2 to columns
6. TRACK 1 for all
7. Utility Ratio 0.9 for all

V. TRANSPORTATION ANALYSIS:

Calculations for time dependent acceleration by Airy's Theory:

Table 1 Required Data to Calculate Acceleration Due to Wave Motion

Parameter	Quantity	Unit
Water Depth h	100	m
Water Density ρ	10	kN/m^3
Water Wave Length L	10	m
Water Wave Period T	30	Sec
Wave Height H	0.5	m
Velocity of Gravity g	9.81	m/Sec
Wave Amplitude (a = H/2)	0.25	m
Wave Number k	0.63	Nos.
Wave Circular Frequency ω	0.21	
Distance from Start of Wave x	2.5	m

Airy's equations for calculation of accelerations:

$$a_h = \frac{\partial V_h}{\partial t} = \frac{H}{2}\omega 2 \frac{\cosh k(h+z)}{\sinh kh} \sin(kx - \omega t)$$

$$a_v = \frac{\partial V_v}{\partial t} = \frac{H}{2}\omega 2 \frac{\sinh k(h+z)}{\sinh kh} \cos(kx - \omega t)$$

Where,

z = a cos (kx - ωt)

a_v = vertical acceleration

a_h = horizontal acceleration av = vertical acceleration

Table2 Time Dependent Acceleration Ah &Av

Wave Period T Sec	Distance from Start of Wave x =	Wave Surface Elevation z = acos(kx - ωt)	Wave surfaceDepth h + z	Inline Acceleration				Vertical Acceleration			
				cosh{k(h+z)}	sinh(kh)	Sin (kx - σt)	Ah m/sec^2	sinh{k(h+z)}	sinh(kh)	Cos(kx - ωt)	Av m/sec^2
0	2.5	1.5314E-17	100	9.6939E+26	9.6939E+26	1	0.011	9.6939E+26	9.6939E+26	6.1257E-17	0.000
1	2.5	0.05197792	100.051978	1.0016E+27	9.6939E+26	0.9781476	0.011	1.0016E+27	9.6939E+26	0.20791169	-0.002
2	2.5	0.10168416	100.101684	1.0333E+27	9.6939E+26	0.91354546	0.011	1.0333E+27	9.6939E+26	0.40673664	-0.005
3	2.5	0.14694631	100.146946	1.0632E+27	9.6939E+26	0.80901699	0.010	1.0632E+27	9.6939E+26	0.58778525	-0.007
4	2.5	0.18578621	100.185786	1.0894E+27	9.6939E+26	0.66913061	0.008	1.0894E+27	9.6939E+26	0.74314483	-0.009
5	2.5	0.21650635	100.216506	1.1106E+27	9.6939E+26	0.5	0.006	1.1106E+27	9.6939E+26	0.8660254	-0.011
6	2.5	0.23776413	100.237764	1.1256E+27	9.6939E+26	0.30901699	0.004	1.1256E+27	9.6939E+26	0.95105652	-0.012
7	2.5	0.24863047	100.24863	1.1333E+27	9.6939E+26	0.10452846	0.001	1.1333E+27	9.6939E+26	0.9945219	-0.013
8	2.5	0.24863047	100.24863	1.1333E+27	9.6939E+26	-0.1045285	-0.001	1.1333E+27	9.6939E+26	0.9945219	-0.013
9	2.5	0.23776413	100.237764	1.1256E+27	9.6939E+26	-0.309017	-0.004	1.1256E+27	9.6939E+26	0.95105652	-0.012
10	2.5	0.21650635	100.216506	1.1106E+27	9.6939E+26	-0.5	-0.006	1.1106E+27	9.6939E+26	0.8660254	-0.011
11	2.5	0.18578621	100.185786	1.0894E+27	9.6939E+26	-0.6691306	-0.008	1.0894E+27	9.6939E+26	0.74314483	-0.009
12	2.5	0.14694631	100.146946	1.0632E+27	9.6939E+26	-0.809017	-0.010	1.0632E+27	9.6939E+26	0.58778525	-0.007
13	2.5	0.10168416	100.101684	1.0333E+27	9.6939E+26	-0.9135455	-0.011	1.0333E+27	9.6939E+26	0.40673664	-0.005
14	2.5	0.05197792	100.051978	1.0016E+27	9.6939E+26	-0.9781476	-0.011	1.0016E+27	9.6939E+26	0.20791169	-0.002
15	2.5	1.5314E-17	100	9.6939E+26	9.6939E+26	-1	-0.011	9.6939E+26	9.6939E+26	6.1257E-17	0.000
16	2.5	-0.0519779	99.9480221	9.3824E+26	9.6939E+26	-0.9781476	-0.010	9.3824E+26	9.6939E+26	-0.2079117	0.002
17	2.5	-0.1016842	99.8983158	9.0939E+26	9.6939E+26	-0.9135455	-0.009	9.0939E+26	9.6939E+26	-0.4067366	0.004
18	2.5	-0.1469463	99.8530537	8.8389E+26	9.6939E+26	-0.809017	-0.008	8.8389E+26	9.6939E+26	-0.5877853	0.006
19	2.5	-0.1857862	99.8142138	8.6258E+26	9.6939E+26	-0.6691306	-0.007	8.6258E+26	9.6939E+26	-0.7431448	0.007

20	2.5	-0.2165064	99.7834936	8.4609E+26	9.6939E+26	-0.5	-0.005	8.4609E+26	9.6939E+26	-0.8660254	0.008
21	2.5	-0.2377641	99.7622359	8.3487E+26	9.6939E+26	-0.309017	-0.003	8.3487E+26	9.6939E+26	-0.9510565	0.009
22	2.5	-0.2486305	99.7513695	8.2919E+26	9.6939E+26	-0.1045285	-0.001	8.2919E+26	9.6939E+26	-0.9945219	0.009
23	2.5	-0.2486305	99.7513695	8.2919E+26	9.6939E+26	0.10452846	0.001	8.2919E+26	9.6939E+26	-0.9945219	0.009
24	2.5	-0.2377641	99.7622359	8.3487E+26	9.6939E+26	0.30901699	0.003	8.3487E+26	9.6939E+26	-0.9510565	0.009
25	2.5	-0.2165064	99.7834936	8.4609E+26	9.6939E+26	0.5	0.005	8.4609E+26	9.6939E+26	-0.8660254	0.008
26	2.5	-0.1857862	99.8142138	8.6258E+26	9.6939E+26	0.66913061	0.007	8.6258E+26	9.6939E+26	-0.7431448	0.007
27	2.5	-0.1469463	99.8530537	8.8389E+26	9.6939E+26	0.80901699	0.008	8.8389E+26	9.6939E+26	-0.5877853	0.006
28	2.5	-0.1016842	99.8983158	9.0939E+26	9.6939E+26	0.91354546	0.009	9.0939E+26	9.6939E+26	-0.4067366	0.004
29	2.5	-0.0519779	99.9480221	9.3824E+26	9.6939E+26	0.9781476	0.010	9.3824E+26	9.6939E+26	-0.2079117	0.002
30	2.5	-4.594E-17	100	9.6939E+26	9.6939E+26	1	0.011	9.6939E+26	9.6939E+26	-1.838E-16	0.000

VI. RESULTS

Different Results obtained from the STAAD.Pro model has been represented here in the form of tables and figures:

A. For full pipe rack (30m) supported on offshore platform:

1. Steel Take Off:

Total steel quantity = 520.56 kN

Table 3 Total Steel Take-off for in-place structure

PROFILE	LENGTH (Meter)	WEIGHT (kN)
ST TUB35035010	91.2	95.281
ST TUB2002006	51.91	19.381
ST TUB35035016	18.74	30.671
ST TUBE	18.74	38.015
ST TUB10010010	38.42	10.478
ST TUB25025010	48	35.214
ST TUB20020010	279.94	162.362
ST TUB35035012	40.97	52.875
ST TUB1001006	195.16	35.082
ST TUB1201206	18	3.941
ST TUB1201208	8.49	2.314
ST TUB80806	48	6.785
ST TUB2002008	60	28.162
	TOTAL =	520.56

2. Sway Check in Xdirection:

Table 4 Sway Check in X direction

Node No	Load Case	Max Displacement (mm)	Frame Height (upper Tier) (mm)	Allowable Displacement H/250 (mm)
331	216	26.179	7600	30.4

3. Sway Check in Zdirection:

Table 5 Sway Check in Z direction

Node No	Load Case	Max Displacement (mm)	Frame Height (upper Tier) (mm)	Allowable Displacement H/250 (mm)
330	209	10.34	7600	30.4

4. Vertical Deflection in Ydirection:

Table 6 Vertical Deflection in Y direction

Beam No	Load Case	Max Deflection (mm)	Member Length (mm)	Allowable Deflection H/400 (mm)
343	110	1.856	3000	7.5

B. **For 30m pipe rack with lifting and transportation analysis:**

1. **Steel TakeOff:**

Total steel quantity = **619.630 kN**

Table 7 Total steel take off of 30m module for lifting and transportation:

PROFILE	LENGTH (Meter)	WEIGHT (kN)
ST TUB35035016	121.94	199.533
ST TUB2002006	51.91	19.381
ST TUB E	18.74	38.015
ST TUB1001006	195.16	35.082
ST TUB25025010	216	158.463
ST TUB20020010	159.94	92.764
ST TUB35035012	40.97	52.875
ST TUB10010010	38.42	10.478
ST TUB1201206	18	3.941
ST TUB1201208	8.49	2.314
ST TUB80806	48	6.785
	TOTAL =	619.630

2. **Sway Check in Xdirection:**

Table 8 Sway Check in X direction

Node No	Load Case	Max Displacement (mm)	Frame Height (upper Tier) (mm)	Allowable Displacement H/250 (mm)
301	201	0.116	7600	30.4

3. **Sway Check in Z direction:**

Table 9 Sway Check in Z direction

Node No	Load Case	Max Displacement (mm)	Frame Height (upper Tier) (mm)	Allowable Displacement H/250 (mm)
305	201	0.221	7600	30.4

4. **Vertical Deflection in Y direction:**

Table 10 Vertical Deflection in Y direction

Beam No	Load Case	Max Deflection (mm)	Member Length (mm)	Allowable Deflection H/400 (mm)
311	101	1.824	3000	7.5

C. For 12m pipe rack module with lifting and transportation analysis:

1. Steel Take Off:

Total steel quantity = **542.785 kN**

Table 11 Total steel take off of 12m module for lifting and transportation

PROFILE	LENGTH (Meter)	WEIGHT (kN)
ST TUB35035010	45.6	47.64
ST TUB35035016	9.37	15.335
ST TUB2002006	18.74	6.998
ST TUB35035012	12	15.487
ST TUB20020010	54	31.319
ST TUB25025010	72	52.821
ST TUB1001006	93.34	16.778
ST TUB10010010	12	3.273
ST TUB1201208	8.49	2.314
ST TUB80806	24	3.392
ST TUB25025012	24	21.755
	TOTAL =	217.114

Equivalent weight for 30m length = 542.785 kN

2. Sway Check in X direction:

Table 12 Sway Check in X direction

Node No	Load Case	Max Displacement (mm)	Frame Height (upper Tier) (mm)	Allowable Displacement H/250 (mm)
331	201	0.142	7600	30.4

3. Sway Check in Z direction:

Table 13 Sway Check in Z direction

Node No	Load Case	Max Displacement (mm)	Frame Height (upper Tier) (mm)	Allowable Displacement H/250 (mm)
323	201	2.766	7600	30.4

4. Vertical Deflection in Y direction:

Table 14 Vertical Deflection in Y direction

Beam No	Load Case	Max Deflection (mm)	Member Length (mm)	Allowable Deflection H/400 (mm)
315	101	1.798	3000	7.5

D. For 6m pipe rack module with lifting and transportation analysis:

1. Steel Take Off:

Total steel quantity = **532.95 kN**

Table 15 Total steel take off of 6m module for lifting and transportation

PROFILE	LENGTH (Meter)	WEIGHT (kN)
ST TUB35035010	30.4	31.76
ST TUB2002006	18.74	6.998
ST TUB25025010	24	17.607
ST TUB20020010	54	31.319
ST TUB1201208	4.24	1.157
ST TUB10010010	6	1.636
ST TUB1001006	29.7	5.339
ST TUB80806	12	1.696
ST TUB2002008	12	5.632
	TOTAL =	106.590

Equivalent weight for 30m length = 532.95 kN

2. Sway Check in X direction:

Table 16 Sway Check in X direction

Node No	Load Case	Max Displacement (mm)	Frame Height (upper Tier) (mm)	Allowable Displacement H/250 (mm)
325	201	0.147	7600	30.4

3. Sway Check in Z direction:

Table 17 Sway Check in Z direction

Node No	Load Case	Max Displacement (mm)	Frame Height (upper Tier) (mm)	Allowable Displacement H/250 (mm)
329	201	0.183	7600	30.4

4. Vertical Deflection in Y direction:

Table 18 Vertical Deflection in Y direction

Beam No	Load Case	Max Deflection (mm)	Member Length (mm)	Allowable Deflection H/400 (mm)
319	101	1.798	3000	7.5

VII. CONCLUSION

The objective of this research was to study offshore steel pipe rack structure using modular design technique. All the analysis and design have been conducted on STAAD.Pro software. In this thesis, we have shown comparison between steel tonnage of conventional and modular structure of steel pipe rack. The results obtained here are showing that we can achieve a considerable economy by using modular design technique. The following summarizes the results and the conclusions.

Contributions of the Present Work:

We had to build a typical offshore steel pipe rack of 30m length, 6m width and 7.6m height at the onshore fabrication plant. And then loading the same on a barge and transport it to the desired offshore platform site.

Basically four different modules were prepared in STAAD.Pro. First module was prepared for full pipe rack supported on offshore platform on which all the different types of loads were assigned. Then second module was prepared for full pipe rack on which only dead load was assigned and lifting and transportation analysis were carried out for the same. Third module was prepared for 12m length pipe rack as per modular design technique and again only dead load was assigned to the same. Then lifting and transportation analysis were carried out for the same. Forth module was prepared for 6m length pipe rack as per modular design technique and again only dead load was assigned to the same. Then lifting and transportation analysis were carried out for the same.

We could observe that when we lift the full pipe rack (30m length) at a time and transport it to the desired location, then the section sizes were tremendously increased as compared to the ones which are provided to the in-place module. Total steel tonnage for in-place structure module was 520.56kN. And total steel take off for full pipe rack along with lifting and transportation analysis was 619.63kN. So the difference in steel tonnage of both was 99.07kN. But when we opted the modular design technique and split the structure in small parts then we observed that almost all the sections assigned to the in-place module were safe to take care of lifting and transportation analysis. So we chose two ways to split the structure such as 12m length and 6mlength.

In 12m length module, the total equivalent steel tonnage for 30m length pipe rack was 542.785kN. So only 22.23kN extra steel is required in this case.

In 6m length module, the total equivalent steel tonnage for 30m length pipe rack was 532.95kN. So only 12.39kN extra steel is required in this case.

So it is very clear now that we can surely achieve a considerable economy in offshore steel pipe rack structure by opting the modular design technique when lifting and transportation come into picture.

VIII. ACKNOWLEDGMENT

I would like to express my sincere gratitude to Prof. Dr. R. S. Talikoti for his excellent guidance and continuous encouragement during course of my work. I truly appreciate for his vast knowledge and delight supervision and advice. My special thanks to Prof. Dr. R. S. Talikoti Head of Civil Engineering Department, for his constant inspiration and all the facilities provided to successfully complete this work. I would also like to thank Prof. Dr. Arun Dwivedi Dean of the Institute who has provided me this opportunity to present this paper. I would also like to thank to all the faculty members of the department for their valuable guidance and support during the course of my work. Also I would like to thank all my friends who have directly or indirectly helped me in my project work throughout the course. Finally, I would like to thank my parents, from whom I learnt the value of hard work and its fruitful results.

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