A Parametric Study on the Structural Analysis, Design and Optimization of RC Bunkers using Sequential Linear Programming

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Abstract— Optimization techniques are powerful tools which convert the problem into a mathematical formulation. There are many types of techniques which are selected based on the type of problem. These techniques can be applied to most of the structural engineering problems to arrive at optimum results. This study involves the development of a C-program for the optimization and analysis of Reinforced Concrete (RC) bunker for various capacities and for various materials stored in it. In this study, the importance of optimization and savings due to it is highlighted. Behaviour of each element of the bunker like side wall, hopper bottom, edge beam etc. is studied with varying capacities and varying material stored in the bunker. The analysis results obtained from the C-program are used for the design of the bunker and the designs are carried out using validated MS-Excel sheets.

Key words: Reinforced Concrete (RC), Bunkers

I. INTRODUCTION

We might remember the older days when the bulk material like wheat, coal, etc. were stored in bags in huge warehouses with an army of labour for loading and unloading them. In modern day, where there is lack of space, time and cheap labour, temporary storage of bulk material has become a costly affair. The only solution to this problem is vertical storage of the bulk material i.e. bins. The bins may be further classified into shallow bins (bunkers) and deep bins (silos). The exact analysis of these storage bins is not possible due to many unknown parameters which affect the actual pressure exerted. Factors such as physical and chemical properties of the material to be stored, influence of change in moisture content and changes in particle sizes, flow pattern required, impact during filling and emptying process, location of discharge hole etc. which cannot be determined exactly and may have considerable effect on design. As we know, in bunkers, the plane of rupture drawn from the bottom side corner intersects the top of the chamber. If the plane of rupture intersects the side wall, it is called silo.

II. DESIGN OF THE BUNKER

The lateral pressure in bunkers is determined by Rankine's theory. The total load of the contents of the bunker is taken to be supported by the floor of the bunker.

A typical bunker is shown in Fig.1. The parts of the bunker to be designed are vertical side wall, hopper bottom, edge beam, column and footing.

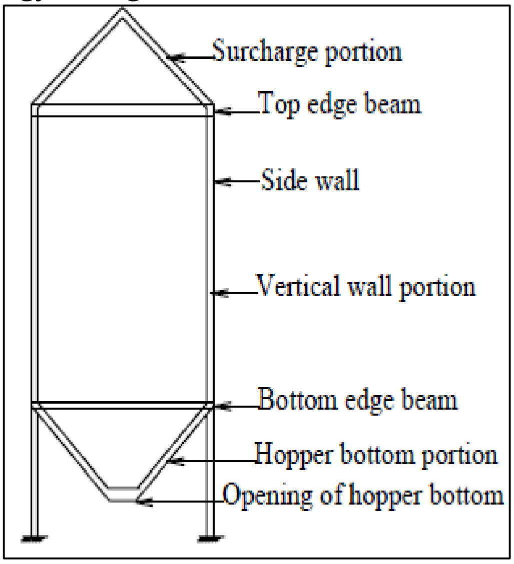

Fig. 1: Typical bunker section

As shown in Fig.2, there are basically three governing forces acting in a bunker namely, horizontal load/pressure (P_h), vertical load/pressure (P_v) and frictional load/pressure (P_w).

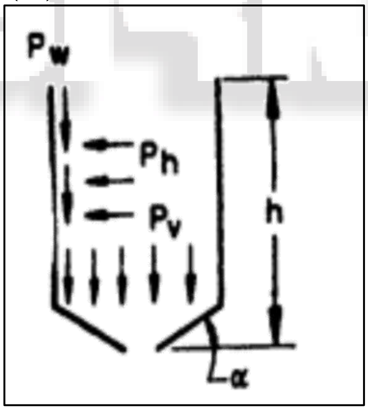

Fig. 2: Pressures acting on the bunker

The exact analysis of pressure is extremely difficult because of many variable factors. Therefore, approximate methods suggested by Janssen and Airy are commonly followed. Airy's analysis is based on Coulomb's wedge theory of lateral earth pressure. By this theory, it is possible to calculate the horizontal pressure per unit length of the periphery and the position of plane of rupture. In this study, Rankine's method is used to determine the horizontal pressure.

A. Fixing Up the Plan Dimensions of the Chamber

$$\text{Vol. of the bunker} = \frac{\text{Total Bunker capacity}}{\text{Unit weight of material stored}}$$

$$\text{Vol. of material stored as surchage} = \frac{1}{3}A'h'$$

Where,

A' is plan area of bunker and h' is height of surcharge

$$\text{Volume of hopper bottom} = \frac{1}{3}(A'h'' - A''h1')$$

Where,
h'' is height of triangular portion joined by the sides of the hopper bottom.
A'' is the plan area of the hopper bottom opening
h1' is height, from the point formed by joining the sides of the hopper bottom till the bottom tip of opening.
Vol. of the chamber = Total Vol. − Vol. of surcharge − Vol. of hopper bottom

$$\text{Height of the chamber} = \frac{\text{Volume of the chamber}}{\text{Plan area of the chamber}}$$

∴Total volume=Vol. of chamber + Vol. of hopper bottom + Vol. of surcharge
Check for bunker action:

$$\text{length} \times \tan\left(\frac{90 + \text{Angle of repose}}{2}\right) > Height\text{ of Chamber}$$

B. Design of Vertical Side Walls

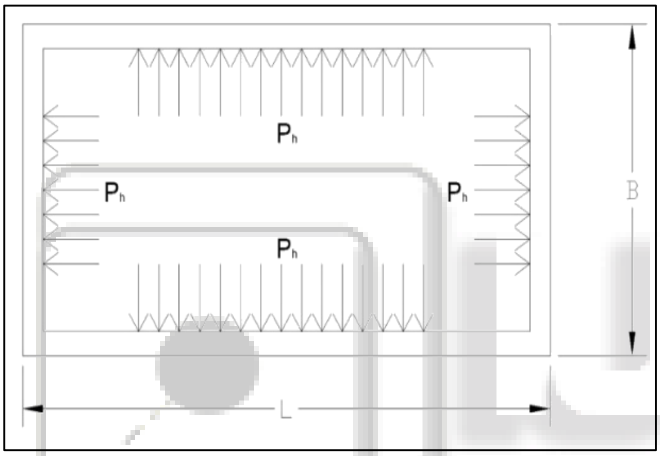

Fig. 3: Horizontal pressure acting on the vertical side wall

The lateral pressure '*p'* exerted by the filling material on the wall is given by Rankine's formula:

$$P = \gamma h \cos\beta \frac{(\cos\beta - \mathrm{sqrt}(\cos^2\beta - \cos^2\Phi)}{(\cos\beta + \mathrm{sqrt}(\cos^2\beta - \cos^2\Phi)}$$

Where,
γ- Unit weight of material stored
h- Depth measured from the top of the stored material
β- Angle of surcharge
Φ- Angle of repose
P_h= P cosβ

$$Ph = \gamma h \cos^2\beta \frac{(\cos\beta - \sqrt{\cos^2\beta - \cos^2\Phi})}{(\cos\beta + \sqrt{(\cos^2\beta - \cos^2\Phi})}$$

Maximum angle of surcharge is naturally equal to angle of repose, which is equal to Φ. In such case,
Ph= $\gamma h\cos^2\beta = \gamma h\cos^2\Phi$
If the top surface is horizontal, β=0

$$Ph = \gamma h \frac{1 - \sin\Phi}{1 + \sin\Phi}$$

Thus the wall is subjected to triangular load increasing with the depth. The boundary conditions are free at top and continuous at the other three edges. Since the height of the wall is less, it is treated as a horizontal continuous beam and hence moments are calculated using the following formulae:

$$\text{Corner negative moment, } M = -\frac{Ph}{12}(L^2 + B^2 - BL)$$

Positive moment at centre of long wall AB and CD

$$= \frac{PhL^2}{8} - \frac{Ph}{12}(L^2 + B^2 - BL)$$

Positive moment at centre of long wall AB and CD

$$= \frac{PhB^2}{8} - \frac{Ph}{12}(L^2 + B^2 - BL)$$

Pressure on the short wall transfer direct tension to long wall,

$$\text{Direct tension in long wall} = \frac{PhB}{2}$$

$$\text{Direct tension in short wall} = \frac{PhL}{2}$$

C. Design of Hopper Bottom

If 'W' is the total weight of the material plus self-weight of the hopper bottom & 'θ' is the angle of the hopper bottom, then:
Tension caused by weight 'W' is given by-
T sinθ = W <u>or</u> T= W cosecθ

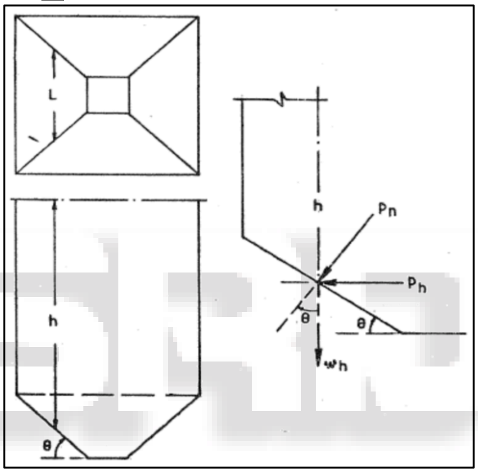

Fig. 4: Bending of sloping slab

For bending moment:
Vertical downward pressure on the strip= γhcosθ
Horizontal pressure on the strip= $P_h$sinθ
Normal pressure on the strip Pn= $\gamma h\cos^2\theta + P_h\sin^2\theta$
Normal component of the self-weight = $W_s\cos\theta$
Total normal pressure, q = $\gamma h\cos^2\theta + P_h\sin^2\theta + W_s\cos\theta$

$$\text{Maximum Negative moment} = \frac{ql^2}{12}$$

$$\text{Maximum Positive moment} = \frac{ql^2}{24}$$

Apart from providing reinforcement for the bending in the hopper bottom, in the design of members subjected to direct tension steel is provided to take full tension per unit width of slab,
Factored Tensile force, T_u= 1.5*T

$$\text{Area of Steel to resist the tensile force, Ast} = \frac{Tu}{0.87fy}$$

$$\text{Tensile stress} = \frac{T}{Ac + m * Ast}$$

Where,
'Ac' is cross-sectional area of concrete
'Ast' is Cross sectional area of steel in tension

$$\text{m is modular ratio} = \frac{280}{3 * \sigma cbc}$$

D. Design of Edge Beams

Edge beams are provided to act as a joint between the side wall and the hopper bottom and between side wall and surcharge portion. At the top, they accommodate the attachment of conveyor supports apart from accommodating the reinforcement in the wall behaving as a deep beam. It also helps in uniform load distribution to the supporting column.

The bottom edge beam is subjected to uniform outward pressure and inward pull from the hopper bottom. The horizontal component of pull from hopper bottom is in inward direction and it is more than outward pressure. However, in bunkers this force is negligible.

Analysis of edge beam involves the calculation of the loads acting on the beam and the moment and shears generated due to them. The dead load of side wall, dead load due to friction between material stored and the contact surface of the wall and total weight of the material stored has to be considered.

Total Load on beam calculated as: DL of side wall + DL of material stored + Self-weight of beam

If B is the one side of the plan dimension,

$$\text{Moment at middle span of beam} = \frac{\text{Total load} \times \text{B}^2}{12}$$

$$\text{Moment at ends of the beam} = \frac{\text{Total load} \times \text{B}^2}{24}$$

$$\text{Shear force at support, Vu} = \frac{\text{Total load} \times \text{B}}{2}$$

It is assumed that beam is being monolithically cast. Beams are designed as flanged beams at mid-span i.e. for positive bending moment. Shear design for beam is carried out as per IS: 456-2000 clause 40.4, spacing of shear reinforcement is determined. This spacing should not exceed the provisions of the relevant code.

E. Optimization

Optimization means the process of choosing the best possible solution from available options. The target of optimizing may be economical design or reduced weight of the structure or a stiffer structure. Hence, the process of optimization depends on the target or the objective intended. Sequential Linear Programming (S.L.P) is a powerful technique for solving complex structural optimization problems. This technique is being used for the optimization of bunker in this study.

III. RESULTS AND DISCUSSIONS

A. Parametric Study by Keeping the Material to Be Stored Constant and Varying The Bunker Capacity

Bunker capacity	Varies as per Input
Concrete grade	25 N/mm^2
Grade of steel	415 N/mm^2
Unit weight of material	8.5 kN/m^3
Angle of repose	28 degrees
Concrete density	25 kN/m^3
Length of the bunker	8m
Width of the bunker	8m

Parameter	Bunker Capacity (kN)						
	250	500	750	1000	1250	1500	1750
Side Wall Thickness (mm)	120	121	150	160	184	190	200
Depth of Edge beam (mm)	230	235	250	270	283	288	280
Shorter Side of the bunker (m)	3.37	4.75	5.5	6.5	7.18	7.93	9.0
Longer side of the bunker (m)	3.37	4.75	5.5	6.5	7.18	8.06	9.0
Total height(m)	4.1	4.85	5.47	5.91	6.34	6.61	6.96
$\left(\frac{h}{b}\right)$	1.23	1.02	0.99	0.90	0.88	0.82	0.77

Table 1: Different parameters of bunker as the bunker capacity is increased

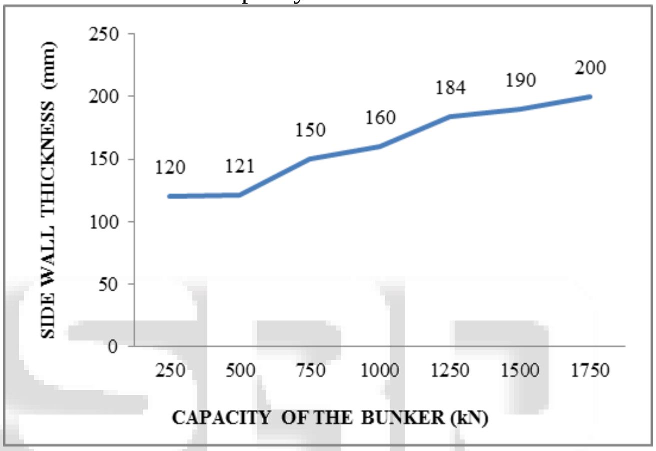

Fig. 5: Variation of side wall thickness along the bunker capacity

In the above plot, it can be seen that the thickness of the sidewall goes on increasing as the bunker capacity increases. This is to resist the increase in horizontal pressure exerted by the material stored.

The following plot shows almost a uniform downward trend of (h/b) ratio against the bunker capacity. It is evident from the graph that as the bunker capacity increases the plan dimension of the bunker increase rather than the height of the bunker.

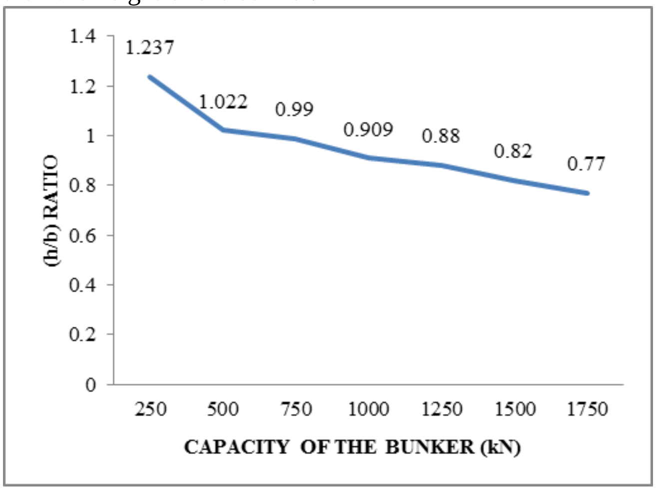

Fig. 6: Variation of (h/b) ratio along the bunker capacity

B. Parametric Study by Keeping the Bunker Capacity Constant and Varying the Type of the Material to Be Stored

Bunker capacity	500kN
Concrete grade	25 N/mm^2
Grade of steel	415 N/mm^2
Unit weight of material	Varies as per input
Angle of repose	Varies as per input
Concrete density	25 kN/m^3
Length of the bunker	8m
Width of the bunker	8m

Materials stored are:

1) Dry, broken loose coke
2) Rice
3) Pulverized & compacted anthracite
4) Raw coal
5) Pulverized fuel, dry and loose ash
6) Cement clinker
7) Lead

Material	1	2	3	4	5	6	7
Bulk Density (kN/m3)	4.3	9.0	9.7	10.4	11.2	16.5	52.5
Angle of Internal Friction(Φ)	30	33	25	40	30	35	35
Side Wall Thickness (mm)	135	120	120	150	128	215	130
Depth of Edge beam (mm)	255	230	230	230	230	230	230
Shorter side of the bunker (m)	5.75	4.25	4.5	3.96	4.0	3.25	3.0
Longer side of the bunker (m)	5.75	4.25	4.5	3.96	4.0	3.25	3.0
Total height (m)	6.45	5.38	4.35	6.04	4.70	4.79	2.95
Total volume(m^3)	116	55.5	51.5	48.0	44.6	30.3	9.52
$(\frac{h}{b})$	1.12	1.26	0.96	1.52	1.17	1.47	0.98

Table 2: Different parameters of bunker as the material stored in the bunker is varied

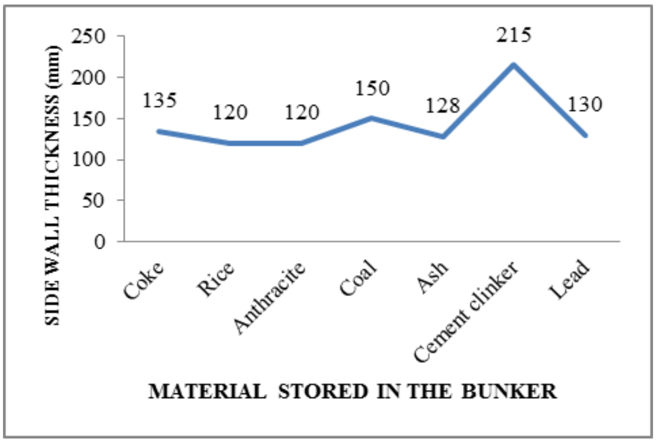

Fig. 7: Variation of side wall thickness for different materials stored in the bunker

IV. QUANTITY ESTIMATION & COMPARISON

Comparisions are drawn on the consumption of the quantity of concrete and steel reinforcement for the construction of the bunker in such a way that for a given bunker capacity, conventional design will be carried out and for the same capacity, optimized parameters will be used for the design and the quantity of concrete and steel are estimated. This gives us a clear picture as to what are the savings by using optimized parameters.

Bunker capacity (kN)	Conventional Design		Design using optimized dimensions	
	Concrete (m^3)	Steel (kg)	Concrete (m^3)	Steel (kg)
250	5.84	363.58	5.34	291.32
500	10.57	773.72	7.49	635.91
750	13.88	921.6	10.68	757.89
1000	17.07	1419.99	15.85	1235.15
1250	23.31	1585.88	21.06	1457.28
1500	27.57	1684.42	24.15	1633.09
1750	37.16	2011.61	36.39	1999.95

Table 3: Comparison of concrete and steel quantity required by conventional design and design using optimized parameters for different capacities of the bunker

Bunker capacity (kN)	% saving of concrete	% saving of steel
250	8.60	19.87
500	26.3	17.81
750	23.1	17.76
1000	7.20	13.06
1250	9.60	8.11
1500	12.4	3.05
1750	2.10	0.58

Table 4: % saving of concrete and steel quantity for different capacities of the bunker

Material stored in the bunker	Conventional Design		Design using optimized dimensions	
	Conc. (m^3)	Steel (kg)	Conc. (m^3)	Steel (kg)
Coke	16.34	1092.43	13.60	969.25
Rice	7.90	677.68	7.30	617.61
Anthracite	9.53	705.12	7.60	601.65
Coal	9.47	566.30	9.00	503.31
Ash	6.93	560.51	6.58	484.54
Cement clinker	10.02	445.15	9.68	377.62
Lead	2.58	341.84	2.51	277.24

Table 5: Comparison of concrete and steel quantity required by conventional design and design using optimized parameters for different material stored in the bunker

Material stored in the bunker	% saving of concrete	% saving of steel
Coke	16.6	11.25
Rice	7.50	8.86
Anthracite	4.90	3.78
Coal	4.40	11.03
Ash	4.10	13.56
Cement clinker	3.40	15.17
Lead	2.60	18.78

Table 6: % saving of the concrete and steel quantity for different material stored in the bunker

V. CONCLUSIONS

1) Various conclusions that can be drawn from the study are:
   When compared to conventional method of bunker design, the design using optimized dimensions yielded the following observations:
   a) Average saving on concrete quantity for different capacities of the bunker is 12.70%.

b) Average saving on steel quantity for different capacities of the bunker is 11.46%
c) Average saving on concrete quantity for different material stored in the bunker is 6.20%.
d) Average saving on steel quantity for different material stored in the bunker is 11.77%.

2) (h/b) ratio decreases as the capacities of the bunker increases indicating the plan sizes increase rapidly when compared to height.
3) Optimal plan of the bunker for different capacities of the bunker is square.
4) Optimal plan of the bunker for different materials' stored is square.
5) Mathematical formulation of structural problems using an appropriate optimization technique can go a long way in making structures more economical and efficient.

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