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Failure of Foundation Systems Using Stone Columns

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SYNOPSIS The paper presents the case history of the failure of a major foundation system comprising of ground improved by stone column technique. An in-depth analysis of the soil parameters, design and construction details, gives valuable lessons for the precautions to be adopted while implementing stone column technique.

1. INTRODUCTION

A Petroleum Company in India constructed four spherical tanks called bullets for storing liquid petroleum gas. These bullets of 18 M dia were to rest on a saucer shaped reinforced concrete foundation. The area where the foundations are constructed has very soft silty clay layers upto a depth of about 11 M. The ground improvement technique by stone columns was therefore adopted to increase the bearing capacity of soil to the required level. Excessive settlements of these tanks occured soon after the construction of tanks and prior to any loading and the total failure

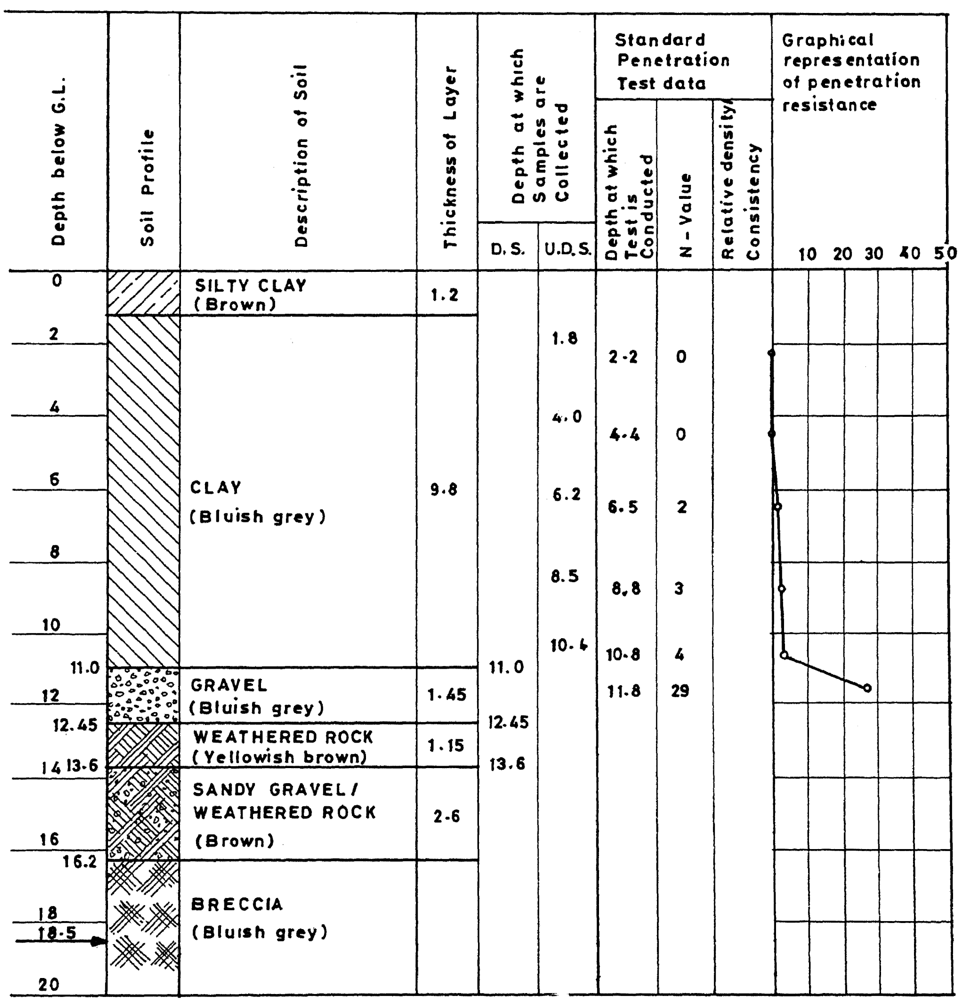

FIG. 1. SOIL PROFILE

by tilting of the foundation system occured when test loading by water was in progress in one of the tanks. The paper deals with the details of soil properties, the design adopted, analysis of the causes of failure and the conclusions made based on the details of the failure.

2. SOIL PROPERTIES

The generalised soil profile of the area where the bullets are constructed is given in Fig. 1. It could be seen that the soil layers upto a depth of nearly 11 M comprise of very soft highly sensitive silty clays followed by clayey gravel with underlying layer of disintegrated rocks. The value of cohesion of the silty clay layer was determined by laboratory vane shear tests, field vane shear tests and triaxial tests. The sensitivity of the clay was determined from the vane shear tests. The range of these values obtained along with the other basic properties like liquid limit, plastic limit and compression index are given in Table - 1.

3. DESIGN OF FOUNDATION SYSTEM

The type of foundation system adopted for the structure is given in Fig. 2. The 18 M dia tank is supported on a 14.4 M dia reinforced concrete raft with a central cup shaped section of 9.9 M dia. The total weight when the hydro-testing of the spherical tank is done is 4500 T. This load with the weight of the foundation, distributed over a dia of 15 M, induces a load intensity of 25 T/M.Sq. The ground was improved with stone columns to a dia of 21.5 M.

The design of the stone column was made by computing the load carrying capacity of each stone column using the lateral deformation theory. The allowable capacity of 90 Cms dia stone column is worked out as 27.5 T. The value of cohesion of surrounding soil considered is 0.2 Kg/Cm.Sq. The factor of safety taken is 1.5. Based on these details, the total number of stone columns required to achieve an improved ground safe bearing capacity of 25 T/M.Sq. is worked out. Accordingly, the spacing of stone column obtained was 1.2 M. The design was finalised based on these calculations with the assurance of settlement of 50 mm under full loading conditions.

Layer	Depth (Metre)	Liquid limit (%)	Plastic limit (%)	C from Triaxial Test kg/cm^2	C from Field vane Shear Test kg/cm^2	C from Lab vane Shear Test kg/cm^2	Sensitivity from field vane Shear Test	Compression Index
SILTY CLAY (Brown)	0 - 1·2	95 - 105	40 - 45	0·1 - 0·18	-	-	-	-
CLAY (Bluish grey)	1·2 - 11·0	100 - 124	40 - 48	0·08 - 0·12	0·03 - 0·3	0·05 - 0·18	3 - 14	0·6 - 0·8

TABLE - 1

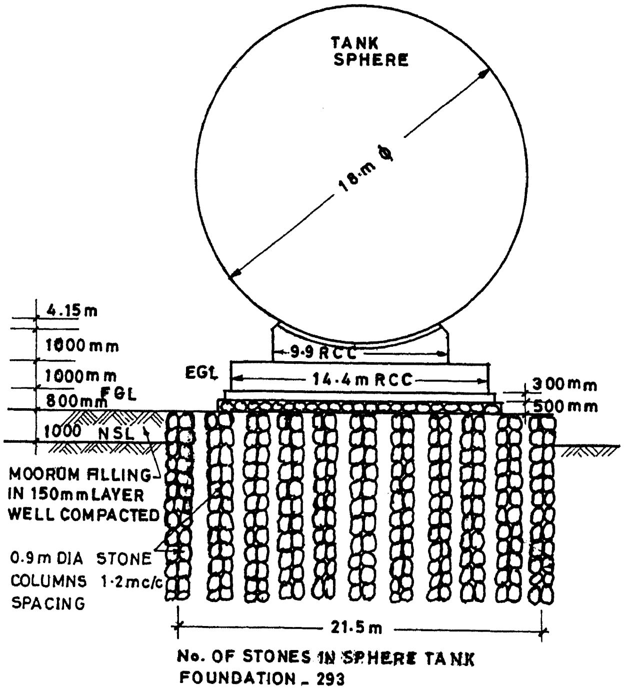

FIG. 2. FOUNDATION SYSTEM

4. CONSTRUCTION TECHNIQUE

The stone column construction was implemented by Vibro-Flotation Technique using the replacement method. The vibrofloat through which water is pumped at high pressure is lowered to the required depth and the cavity created is filled with 20 to 70 mm size granite stone chips. The float size of 35 to 37 Cms gave a stone column diameter of 90 Cms.

5. LOAD TEST ON STONE COLUMNS

The load tests on stone columns were conducted using a single column and a group of three columns. The load settlement patterns as obtained are given in Figs. 3 & 4. From the results, it is seen that the settlement obtained is as required within 50 mm under the prescribed loading rate.

6. FAILURE OF THE STRUCTURE

The differential settlements to the tune of 50 to 60 mm and the total settlements of the order of 300 mm occured

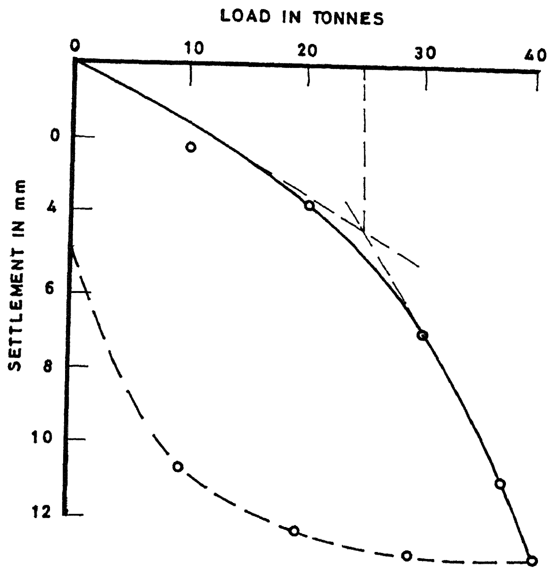

FIG.3. LOAD TEST ON SINGLE COLUMN

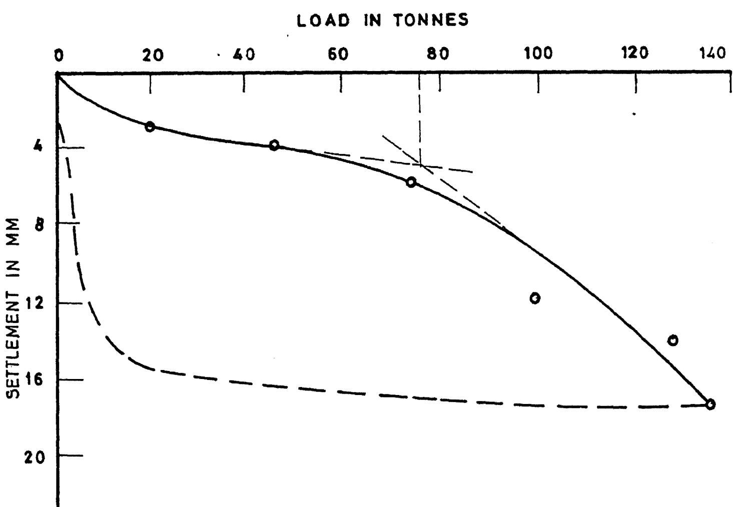

FIG.4 LOAD TEST ON 3 COLUMNS

in the tank foundations soonafter the fabrication of the tank on the RC raft was completed. However, since the differential settlements were not alarming at this stage, one of the tanks was subjected to stage loading by filling the tank with water. When the tank was nearly half-full with the load intensity of the order of 12 T/M.Sq. on the soil, the complete raft system tilted to one side and the entire tank collapsed and rested on the ground as indicated in Fig. 5.

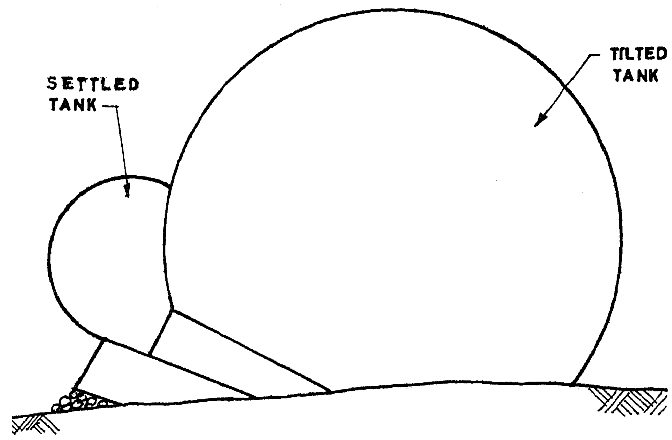

FIG.5. FAILURE OF TANK

7. ANALYSIS OF THE CAUSES FOR FAILURE

a) Design:

For the design of the capacity of the stone column, initial value of cohesion of 0.2 Kg/Cm.Sq. is considered. This value was taken as an average value from the field vane shear tests. Many of the observed test values were less than 0.2 Kg/Cm.Sq. The laboratory vane shear test gave an average value of cohesion of 0.1 Kg/Cm.Sq. The value of cohesion taken as N/10 Kg/Cm.Sq., where N is the standard penetration test value gives the values less than 0.1 Kg/Cm.Sq.

b) Sensitivity Of Clay:

The sensitivity of the order of 3 to 14 has been observed for the silty clay in which the stone columns were constructed. This factor was not considered in the design. In sensitive clays the minimum spacing required between the stone columns has to be 2 M, whereas in this case the sapcing available was only 1.2 M. The factor of safety that should be adopted in sensitive clays has to be 3 against which a value of 1.5 was adopted.

c) Limit Capacity Of Stone Column:

Adopting the theory given by Hughes and Wither and also Mc Vicar as given in Fig. 6, the maximum ultimate capacity to which the ground could be improved is only 25 times its original value of cohesion. Considering that actual failure occured at 1.2 Kg/Cm.Sq., the corresponding value of cohesion which was active is of the order of only 0.05 Kg/Cm.Sq. In many of the shear tests, C-values of this order was actually noted.

According to the theory by Smoltzyk (Ref. Fig. 7), it could be seen that the ground improvement would not be effective when the initial value of cohesion is less than 0.1 Kg/Cm.Sq. In this case the clay layer in many sections had values of cohesion less than 0.1 Kg/Cm.Sq. and hence probably the choice of stone column technique itself is not justified.

d) Errors In Load Test:

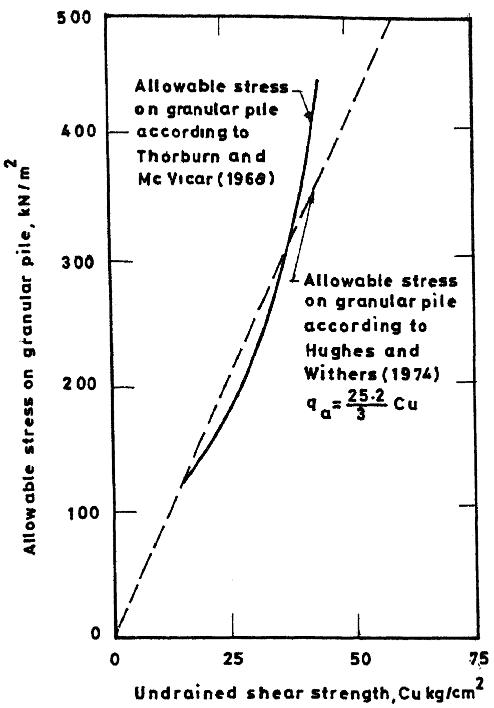

FIG. 6. DESIGN CURVES

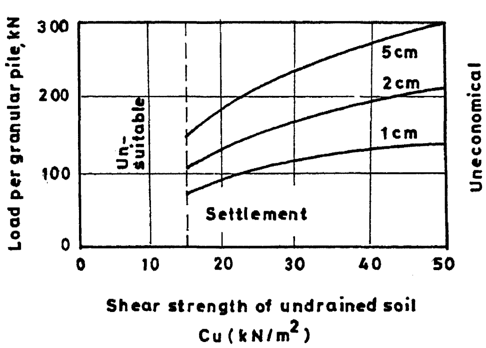

FIG. 7. SUITABILITY OF SOIL FOR STONE COLUMNS

The load test of stone column by testing one or group of three columns does not fully represent the actual loading condition. The load tests are done for a period of 24 hours, whereas considerably more time is required for the settlements to take place. It could also be seen from the load settlement curves (Ref. Figs. 3 & 4) that failure mode has set in at a stage when capacity of 25 T per column. This factor was not observed in the analysis of the results. The fact that actual settlements under loading were much more than the settlements observed in the load test clearly shows the load tests on stone column do not represent the actual behaviour pattern.

e) Net Settlement Of The Ground:

The stone columns could effectively reduce the settlement due to the consolidation of the ground by a maximum of 60%. The settlement of the untreated ground due to the loading of 25 Kg/Cm.Sq. over a diameter of 15 M is worked out as about 600 mm. The settlements that should be expected after the construction of stone column would thus be 180 mm. This factor was not taken in the design.

8. LESSONS FROM THE FAILURE

From the failure of the ground improved by stone columns, the following major observations may be made:

i) Ground improvement irrespective of the spacing of the stone columns could be done only to an ultimate value of 25 times the value of cohesion of surrounding soil.

ii) In sensitive clays extreme care has to be taken to restrict the spacing of column to 2 M and the factor of safety of 3 has to be always adopted in such clays.

iii) When the designs are made, proper weightage has to be given for the lower values of the soil parameters observed in the tests.

iv) In very sensitive clays, vibro-flotation technique is likely to generate disturbance to the soil, thus considerably reducing the value of cohesion.

v) The net settlement of the ground even after the stone columns are provided should be taken as nearly 30% of the settlement of the ground without improvement.

vi) Attempt should not be made to improve the capacity of soft clay layers using stone columns when the initial value of cohesion is less than 0.1 Kg/Cm.Sq.

vii) Test loading of a few stone columns would not correctly represent the behaviour of the entire improved ground under full loading.

9. CONCLUSIONS

Eventhough the stone column technique is a very useful tool when the bearing capacity of the soil for a large area has to be improved, one has to carefully consider the nature of the soil and determine whether it is suitable to be developed by stone column technique. Very sensitive soft clays normally are not suitable for improvement by the stone column techniques. The settlement of the ground even after the stone column is adopted should be within the permissible limits for the structure proposed.

10. REFERENCES

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