Behaviour of Foundations on Stone Column Treated Ground

Comportement des Fondations sur Colonnes en Pierre

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SYNOPSIS: Use of stone columns, sand drains and preloads enabled improvement of ground to bear very heavy foundation loads at the Kandla Fertilizer Plant site situated in Western India where a large depth of soft compressible deposit exists. This paper describes the approach used for selection of a combination of techniques of preloading and stone columns used in various situations. Theoretical concepts used for optimisation of the foundation systems are described briefly and limitations of the design approach are discussed. Field experience of three different types of structures where different combinations of stone columns, sand drains and preloading have been used is presented. Performance of the foundations of these structures is compared with the predicted behaviour in each case.

1. INTRODUCTION

Although several applications of compacted granular columns (stone columns) for ground improvement have been reported (Greenwood 1970, Geotechnique Symposium 1975) data on performance of treated ground and structures supported thereon are scanty. In an earlier paper (1975) the authors described the method of installation adopted at the Kandla Fertilizer Project viz: ramming within a cased bore hole and presented field data from large scale load tests. In this paper observational data are presented with respect to foundation behaviour of some structures along with a brief summary of the design approach for optimising the system of ground improvement.

2. THE PROJECT

Structures and equipment in the Kandla Fertilizer Complex can be categorised as :
(i) Structures supporting heavy equipments such as the manufacturing and bagging units which would not tolerate any settlement
(ii) Bulk storage facilities with loading and unloading equipment and conveyor systems which support heavy load but can be designed to tolerate settlement (iii) Phosphoric acid and other storage tanks with related piping and pumping units and pipe racks which can tolerate considerable total and differential settlement (iv) Ware house, machine shop and administrative buildings designed to tolerate anticipated settlements. Fig.1a shows the plant layout.

3. THE SUB-SURFACE CONDITIONS

The sub-surface conditions and soil characteristics are shown in Fig. 1b, Fig.1a shows the bore hole positions. There is a large depth of highly compressible marine clay and silt of low shear strength. The site has been developed by filling to an average 2 metre depth. Firm strata capable of supporting piles is available at a depth of 20 metres.

4. CHOICE OF FOUNDATIONS

The plant site is located in an area of high seismic activity. Choice of precast driven piles was restricted on economic grounds to foundations supporting equipment and related buildings which would not tolerate settlement.

For ground improvement the following combinations of measures were considered :
(i) Installation of sand drains with or without stone columns followed by preloading
(ii) Preloading after installation of sand drains which was followed by installation of stone columns (iii) Providing sand drains and stone columns without preloading.

Sand drains followed by preloading were employed when design load intensities were moderate so that preloading with earth fill was practicable. Effectiveness of preload on areas of limited extent was improved by installing stone columns below the foundation area.

Where design load intensities were very high, requiring large preload fills, it was convenient and economical to partially preload the ground after installation of sand drains. Subsequently stone columns were installed so as to achieve the required bearing capacity and restrict the settlements to planned limits.

Where dead weight of structures constituted a major part of the load, stone columns and sand drains were installed without preloading. Structures were suitably articulated in order to tolerate movements during construction and completion of consolidation. These joints were grouted or welded after an initial observation period in order to achieve desired stiffness and stability against wind, crane-loads and the like.

5. ESTIMATION OF BEARING CAPACITY AND SETTLEMENT

For purpose of estimating the bearing capacity of improved ground a design parameter, such as the capacity of a column defined as the load on a group divided by the number of columns was estimated on the basis of the following alternate theories : (i) Groups of stone columns tending to yield laterally were considered to be supported by passive resistance of the surrounding ground (ii) The columns derive their support from the resistance to cavity expansion caused by the uncemented bulging column. Vesic's (1972) cavity expansion factors for the expansion of cylindrical cavities in infinite soil mass was used (iii) Energy concept where the driving set during ramming was correlated to the short term capacity of the column. Validity of these estimates were checked by load tests which also provided data for evaluation of the insitu deformation characteristics of improved ground. Observed settlement from a small group load test was used to extrapolate the settlement of larger groups as for incompressible piles. Parameters for strain compatibility analysis were derived from large group tests by making a conservative estimate of the load shared by stone column.

Stability of improved ground was estimated on the basis of assumed load sharing between the soil and the column for vertical strain compatibility and considering the columns to act as shear pins.

6. PERFORMANCE OF STRUCTURES AND FOUNDATIONS:

i. Bulk store building: Fig.2 shows the bulk store building, a typical case of category ii alongwith the arrangement and spacing of sand drains and stone columns. Maximum intensity of pressure on the floor at the centre of the storage heap was 13.2 tonnes per square metre. The ground was preloaded to this intensity after installing stone columns and sand drains. Table 1 summarises the results of stability computation which reveals the danger of slip even in the preloaded ground. The benefits of stone columns is also clear from the table.

TABLE 1 : Factor of Safety against failure. (Bulk Store Building).

Ground condition	Factor of safety of Storage heap		Divider wall	
	i	ii	i	ii
Virgin ground	0.727	0.61	0.66	0.67
Preloaded ground	0.975	0.90	1.05	1.07
Stone columns only (neglecting strength gain)	1.40	1.36	1.72	1.74
Stone columns and preload.	1.65	1.62	2.12	2.01

NOTE:- i circular arc ii block failure.

The structures were designed to tolerate an anticipated residual settlement of 120 mm. The structure is now in service for two years. No slipping or heaving had been observed under the preload fill neither has there been any slipping or heaving of the floor or tilting of the divider walls or at the toes of the product heap. Maximum observed settlements under the structural foundations is 34 mm. No perceivable differential settlements have been observed.

ii. Phosphoric Acid Tanks : Fig.3 shows the details of these tanks typical of category iii structures alongwith the arrangement of stone columns and sand drains. Each tank is designed to hold 10,000 tonnes of acid exerting a maximum pressure of 20 t/m^2 on the floor. Preloading to this intensity was not practicable because of the large height of preload fill and the possible shear failure of the virgin ground. The ground was preloaded to half the design intensity after which the stone columns were installed. Since the verification of design assumptions under critical loading conditions was not possible because of reduced preloads, certain built-in reserves such as conservative estimate of settlements and provision for corrective measures for any departure from the anticipated behaviour was also made. The tanks are in service under full operating acid loads for two years. Table 2 shows the observed settlements and the anticipated values. The rate of settlements at the time of reporting is practically negligible. Neither the built-in reserves have been called into play nor corrective measures have been necessary.

TABLE 2 : Phosphoric Acid Tank Settlements.

	Settlement mm Anticipated*	Observed*
1. Max.peripheral	300*	243*
2. Differential i) in any 45° segment.	50	56
ii) Edge to centre	350	not available.

NOTE:- * Allows for settlement of sand pad + soil below treated zone.

iii. Pipe racks and conveyor supports: These formed a special case. Foundation widths of these supports are narrow but the dead weight of the structure constituted a major part of the load. Isolated piles would be uneconomical for such situations and also they would attract large negative skin friction drag forces due to the settlement caused by the general fill. It was decided to install stone columns and sand drains but omit preloading. The fill drag constituted a virtual preload and the incremental settlement due to the

Fig 1a Plant layout & bore hole positions

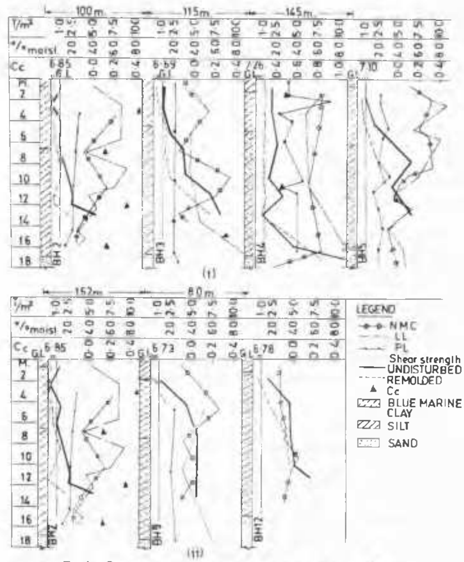

Fig 1b Subsurface conditions & soil properties
(i) Section along BH2 BH3 BH4 & BH5
(ii) Section along BH2 BH9 & BH12

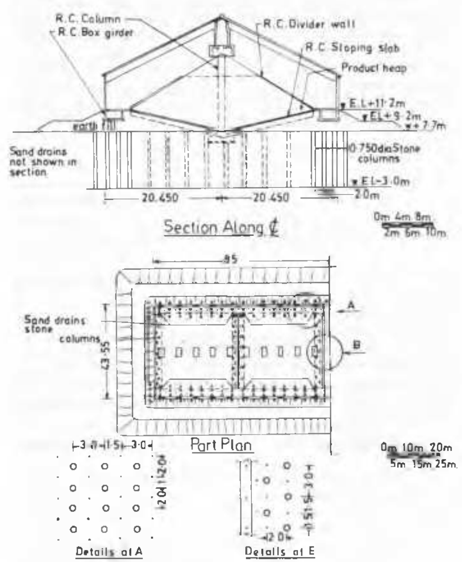

Fig 2 Bulk store building foundation

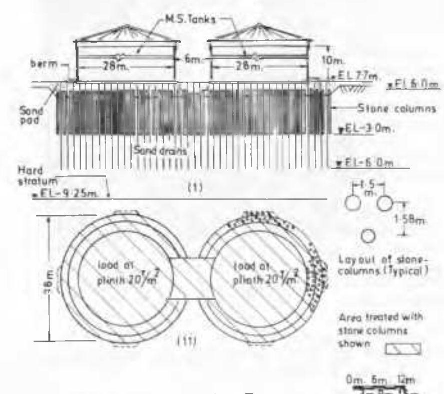

Fig-3 Phosphoric Acid Tank Foundations
(i) Section (ii) Plan

weight of the supports was very small. This additional settlements in pipe racks was completed within 3 weeks by which time the supports were adjusted and grouted. Observations over the past two years show that the maximum settlement of the pipe racks has been 15 mm. and there has been no service disruption because of failure or differential sinking of the supports. In conveyor supports since there was need for adjustment the same approach was followed but without any provision for grouting.

iv. Ware house and machine shop: In this structure the drag induced by virtue of the relative rigidity of stone columns enabled high preload intensity to be achieved over the footing foundation without increase of overall height of preload fill. Although precise observations of total settlement are not available, there are no cracks in walls nor is there any perceptible differential settlement.

7. CONCLUSIONS

The observed behaviour confirms the estimate of settlement and bearing capacity. If proper sequence of installation of stone columns, sand drains and preloads are used in suitable combinations a high degree of ground improvement can be achieved and settlements could be reduced to a small fraction of the settlement of virgin ground under comparable loading intensity.

In conclusion it can be stated that ground improvement by use of stone columns is amenable to rational design analysis inspite of the limitations of theoretical basis of design adopted comprising cavity expansion theory, assumptions of strain compatibility and similitude concepts for group settlement analysis.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

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Appendix - I

<u>Capacity of a 75 cm. nominal diameter stone column</u>

Methods of analysis used are briefly explained below:

i. <u>Lateral Earth pressure theory</u>-Closely spaced stone columns arranged in a parallel array or covering a large area in plan are assumed to behave like a continuous retaining wall and analysed as two dimensional plastic failure case.

ii. <u>Cavity Expansion</u>- The critical zone for this type of a failure is considered to be the top layer having the min. value of cohesion. The pressure required to cause the expansion of a cylindrical cavity at 4 metre depth is estimated using vesic's cavity expansion theory (Pu=cF'c+qF'Q). F'c and F'q are selected for two cases of saturated clay viz.soft (Ir=10) and stiff (Ir=300) c=1.0 t/m 2 (based on vane shear test). ϕ=0 (end of construction case) γ=0.9t/m^3 Area of column as installed is 0.7088m^2 The limiting vertical stress in the column material is assumed 6 times this radial stress.

iii. <u>Energy concept</u>- For correlation of the driving set to driving energy R=nwh/s is used with a low value of n (=10%) selected initially which was back checked on the basis of resistance measured in field load tests, which gave n=5% for the max. load applied in the test. The columns, however, have not been tested to failure. Energy losses due to temporary compression of the column and soil are not separately accounted for. Due to repeated ramming and the consequent increase in the modulus of elesticity, the temporary compression of the column can be assumed to be negligibly low. The error due to neglecting these two factors is not more than about 10%. Results of calculations based on the above theories are tabulated below:

Table - Capacity of 75 cm. stone column

Method of Analysis	ultimate load tonnes	
	a	b
Lateral Earth Pressure	47	37
Cavity Expansion	41 to 61*	25 to 40*
Energy concept (For a set of 5cm/20blows)	90	

'a'-Accounts for strength gain due to pre-load, 'b'-Capacity on virgin ground, * Min. and max. values based on rigidity index for soft and stiff clay respectively.