The recent advances in design and execution of stone column foundations

Les progrès récents du projet et de l'exécution des fondations sur colonnes de gravier

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SYNOPSIS : During the last 25 years, the stone column technique for ground improvement has found wide application in many countries including India. During this period, India has contributed greatly in development of this technique, both in design and execution. Rammed stone columns, preassembled stone columns and skirtted stone columns have been basically developed by Indian Engineers. Rammed stone columns and preassembled stone columns are found to be functionally superior to vibro replacement stone columns adopted in developed countries like Europe and America.

Extensive application of stone column foundation system in Indian practice alongwith testing and monitoring has given the confidence that the performance of stone column foundation system can be predicted as reliably as for rigid concrete piled foundation.

India has introduced new concept in load testing. It load tests the composite system of stone column and the surrounding soil. Such load test results are found to be useful parameters in estimating settlement of structures resting on stone column foundation system.

INTRODUCTION

The stone columns were well known in France in the year 1830's and they have been re-discovered since last 25 years or so. Since then this technique has found wide application in many countries including India.

In developed countries, the stone columns are formed by vibratory poker known as vibroflot. However, since the vibroflot is an imported equipment, Indian engineers had to adopt to innovations resulting in alternate method of execution. This has resulted in development of "rammed stone columns" and "preassembled stone columns", which are described later in this paper.

This paper also describes other innovations and contributions made by Indian engineers in application of this technique. The Indian contribution, both in design and construction aspect of stone columns is described in this paper.

RAMMED STONE COLUMNS

As in developed countries, in India also initially vibroflot equipment was used for installation of stone columns. However, vibroflot is an imported equipment in India. The import policy of Government of India coupled with lack of enthusiasm of Indian Industry to develop such an equipment compelled Indian engineers to look for alternative method of installation. This resulted in development of rammed stone columns.

For installation of rammed stone column, primitive piling equipment used in installation of bored cast insitu piles are used. Thus the equipment consists of tripod, bailer, rammer, winch and casing. Fig.1 illustrates this method of execution. Introduction of any new concept is generally resisted. For acceptance of new concept, it is essential to prove that the product achieved from new methodology is technically superior and also economical.

Critical study of the methods of installation of stone column by both the methods would reveal that rammed stone columns have to be functionally superior to vibro-replacement columns. In vibro replacement column, the stone backfill is compacted by applying horizontal centrifugal force. This may help in achieving bigger diameter of stone column compared to vibroflotted hole, but interlocking of particles of stone backfil will not be as good as in rammed columns. In rammed columns backfill is compacted by falling weight of the hammer, resulting in better interlocking of the particles. This has been convincingly proved by Datye and Nayak after carrying out extensive works. Datye (1983) has shown that verticle yield stress parameter $F'S_c$ is higher by about 70% for rammed stone columns compared to vibro replacement stone columns. Higher value of this parameter means higher yield strength of the stone column.

Nayak (1985) has shown that for rammed stone columns angle of internal friction of the backfill can be considered close to 45° whereas angle of internal friction is of the order of 38° for the vibro replacement columns.

Close examination of the two methods would reveal that drainability of rammed stone columns is far greater than that of vibro replacement columns in which soil slurry gets mixed up with backfill to a great extent.

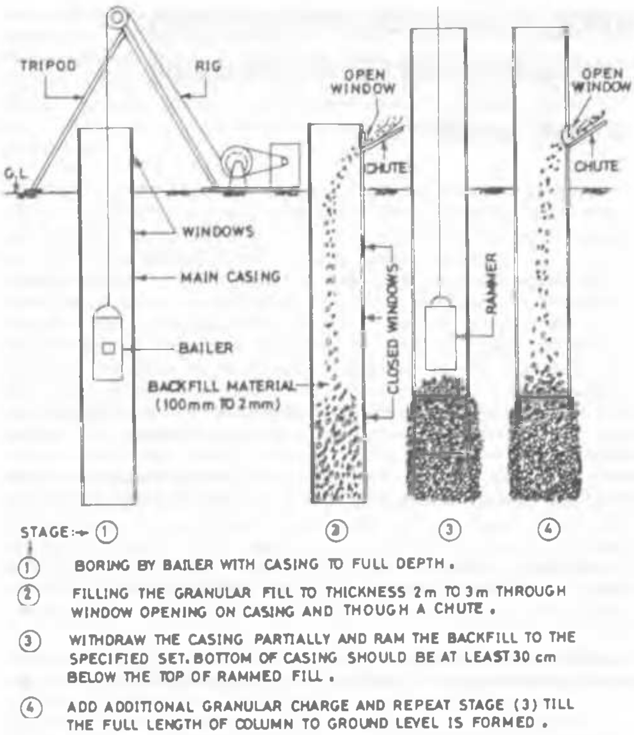

Fig.1: Stages of Construction of Rammed Stone Columns by Piling Equipment

The major advantage of the vibroflot equipment is the speed of execution. It was observed that the production by vibroflot in terms of meterage of stone column installed is equivalent to that achieved initially by 20 to 25 piling rigs used for rammed stone columns. Hence from economic consideration, the Indian engineers were compelled to achive higher production per rig for rammed stone columns.

After extensive experimentation on method of installation of rammed stone columns, the following methodology is found to give optimum production.

For stone columns of 6m or less length, a single piece casing is utilised, so that no time is lost between de-assembling and assembling the different pieces of the casing. However, the casing is provided with flap door windows (Fig.1) at depth interval of 1½ to 2m, so that the backfill can be charged into the borehole through these windows. For stone columns longer than 6m, it was essential to use casings in pieces. For this purpose, specially designed "Male and Female (Fig.2)" couplings were designed. With these couplings, it was possible to join and deassemble the pieces in a short period of less than a minute. As a result, casing pieces were made of 2m length, so that charging of backfill is done as soon as each piece is removed.

PRE-ASSEMBLED STONE COLUMNS

The need for high production per rig has resulted in development of preassembled stone columns. In this method, stone columns are preassembled on ground in bamboo cages of required diameter and then lowered in prebored holes (Fig.3). Thereafter ramming of the stone aggregate is carried out by hammer as is done for rammed stone columns.

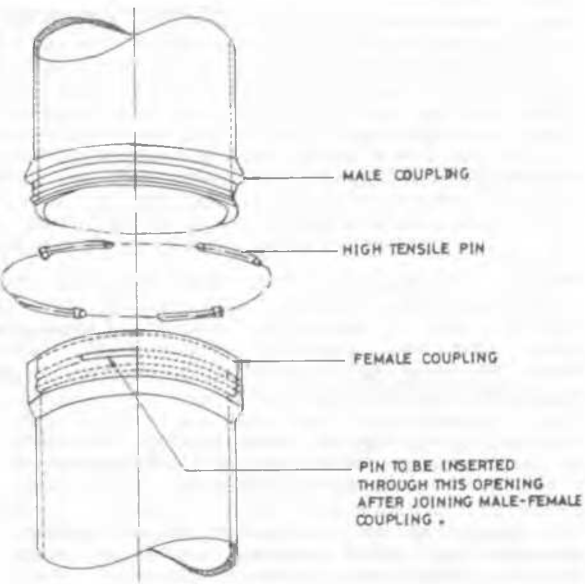

Fig.2: Male Female-Coupling

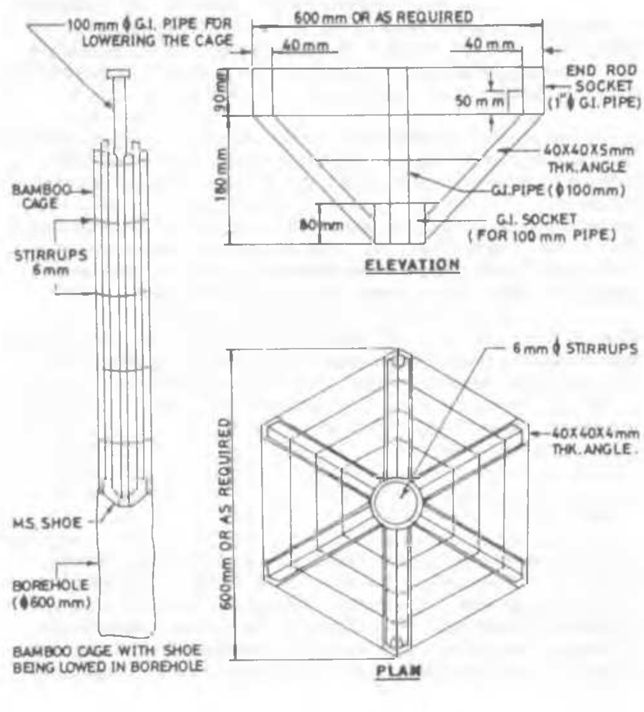

Fig.3: Preassembled Stone Column with Bamboo Cage, Shoe, Stirrups etc.

Limited studies have indicated that performance of these preassembled stone column is almost as good as rammed stone columns. But the speed of execution is faster.

YIELD STRENGTH

The precise mathematical analysis for the yield strength is not possible. However, based on extensive application, semi-empirical approach has been developed by the author. Extensive load testings, monitoring etc. has indicated that with the approach suggested by the author it is possible to predict yield strength of stone column as confidently as one is capable today to predict the performance of rigid pile foundation. The stone column derives its support mainly from the following four components:

a) resistence offered by the surrounding soil against lateral deformation (bulging) of stone column under axial load,

b) bearing support provided by soil in between the stone columns,

c) increased resistence to lateral deformation due to surcharge on the surrounding soil,

d) increased capacity from components (a) to (c) above, resulting from dissipation of excess pore water pressure through stone columns which act as drainage paths.

In Fig.4 results of the load tests conducted on some of the stone columns are plotted. On the same figure, values of yield strength estimated by above theory have also been indicated. Comparison of these results indicate that actual failure load varied within ±8% of the estimated value, thereby indicating good reliability of the approach suggested by the author.

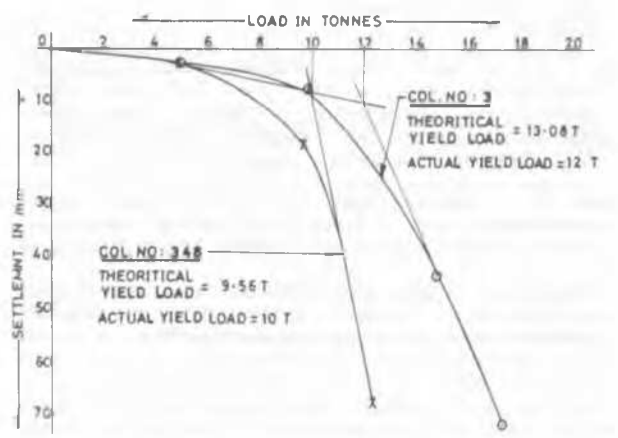

Fig.4

LOAD TESTING

The load test arrangement developed in India differs greatly from that adopted in other countries. In the Indian practice, the composite system i.e., the stone column along with surrounding soil is load tested (Fig.5). It can be seen that the approach for load testing adopted by the Indian engineers is more appropriate to predict the behaviour of stone column and soil system.

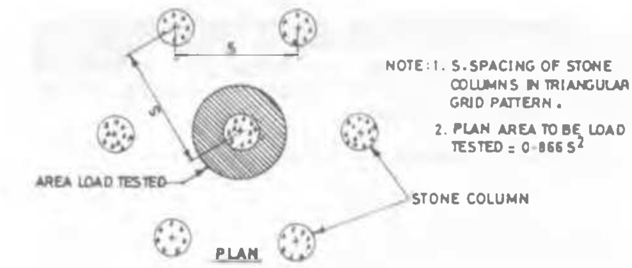

Fig.5: Author's Approach for Load Test on a Single Stone Column

To predict the behaviour under horizontal loading of the stone column, the lateral loadings arrangement as shown in Fig.6 is adopted. The arrangement is shown for lateral load testing on a pair of single columns and also on a pair of group of two columns. Limited tests conducted have indicated that angle of internal friction of backfill of vibro-replacement stone columns under lateral loading is generally in the range of 38° which corresponds closely to value obtained under vertical loading for such columns.

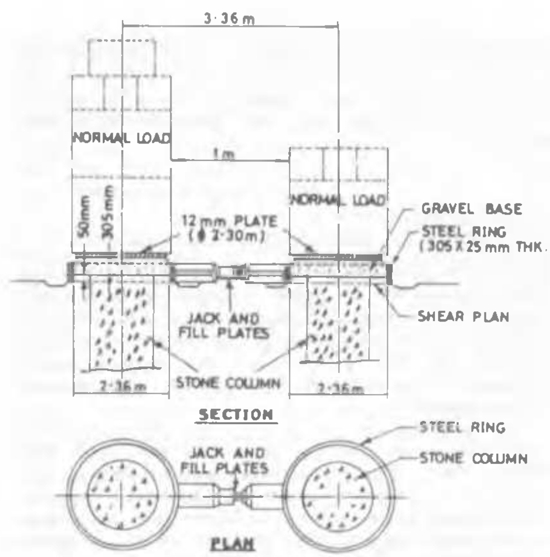

Fig.6: Horizontal Load Test on a Pair of Single Columns

SETTLEMENT ESTIMATE

The theoretical approaches are available for estimating the settlement of structures resting on stone column foundation system. In the theoretical approach, certain values for modulus elasticity of the stone column and the surrounding soil are assigned. Alternately settlement is estimated using the concept of equivalent coefficient of volume compressibility of the composite mass of soil stone column system (Rao et al 1985).

Extensive testing in India has indicated that actual settlements observed are generally far less than estimated by above theoretical approach thereby probably indicating that values assigned for modulus elasticity are extremely low. However, results of extensive load testing and monitoring of settlement of actual structures founded on stone columns have enabled in developing an empirical equation for estimate of settlement of structures resting on stone column foundation system.

The equation proposed by the Author is :

$$\frac{S_f}{S_p} = \left[\frac{B_f}{B_p} \cdot \frac{S^2}{D^2} \cdot \frac{D_t}{D} \right] I$$

where

S_f = Settlement of foundation on stone column system at design load, (mm)

S_p = Settlement of stone column under load test at design load, (mm)

S = Spacing of stone column, (m)

D = Diameter of stone column, (m)

D_t = Depth of treatment, (m)

I = Empirical factor.

In the studies conducted by the author, the empirical factor 'I' was found to vary between 0.06 to 0.10 with an average value of 0.08.

The above equation is applicable if stone columns are installed to full depth in soft clay. Thus it is presumed that the strata below the terminating depth of stone columns do not contribute to settlement of foundation.

OTHER DESIGN GUIDELINES

In the initial Indian practice, the backfill of stone column often consisted of stone aggregates and sand. However, it has now been established that the backfill need not contain sand and size of the stone aggregates can vary from 100 mm to 5mm. In fact excess use of sand is found to decrease the angle of internal friction of backfill.

Similarly earlier high energy of compaction was used in compacting the backfill. This was done on the understanding that higher angle of internal friction will be achieved. It is now realised that excessive application of energy crushes the particles of stone aggregate resultng in low angle of internal friction. After extensive work a "set" criteria has been established to achieve the optimum result. The satisfactory compaction is considered to be achieved when the "set" of 17mm or less is obtained for ten blows with each blow imparting 20 joules (2 tonne-metre energy).

CONCLUSIONS

Rammed and preassembled stone columns are developed by Indian engineers to meet the socio-economic needs of the country. They are found to be functionally superior to vibro-replacement stone columns. In rammed columns the energy of compaction needs to be judiciously selected.

In Indian practice composite system of soil-stone column is tested and such test data can be profitably utilised in realistic prediction of settlement of structures resting on ground improved by stone columns.

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