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STONE COLUMNS

COLONNES DE PIERRE

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SYNOPSIS: Installation of stone columns is one of the most versatile techniques for improving soft, compressible and weak ground with soils ranging from loose sands to soft clays. They provide both the reinforcing and drainage functions, and in addition, densify in situ soils. In this report, (i) the failure mechanisms, (ii) the effect of dilation of stone column material on settlement reduction, (iii) the stress transfer through stone columns and (iv) the liquefaction damage mitigation effects, are discussed. Bulging and pile failure mechanisms are not mutually exclusive but should be considered together. Consideration of even 0.5% dilation of granular material leads to larger settlement reductions. Stone columns function as compressible piles and transfer some of the load applied on them through shaft resistance. Not only the drainage aspects but also the reinforcing effect contributes to the mitigation of damage from liquefaction and post liquefaction displacements of points one to two diameters from the stone columns.

Amongst the various techniques for improving in situ ground conditions, stone columns or granular piles are probably the most versatile. They provide the primary functions of reinforcement and drainage, and in addition, improve the strength and deformation properties of the soft soil in the post installation and reconsolidation phase. Stone columns increase the unit weight of the in situ soil, drain rapidly the excess pore pressures generated and act as a strong and stiff elements and carry higher shear stresses. They are installed in a wide variety of soils, ranging from loose sands to soft compressible clays. The rammed stone column technique (Datye and Nagaraju, 1975) incorporates the additional benefits of heavy tamping as the installed stone column is in effect preloaded. Stone columns are becoming the preferred choice to mitigate damage from liquefaction (Baez and Martin, 1992) and minimize settlements following it. Bergado et al. (1991) present the most recent state of art report on this topic.

For a single stone column, bulging, general shear and pile failure mechanisms are postulated as normally possible ones. For most granular piles whose lengths are greater than the critical length, it is recognized that the bulging failure is the controlling mechanism whether they bear on a stiff layer or penetrate partially into medium stiff soil. However, it should be noted that bulging and pile failure mechanisms are not mutually exclusive. While the tendency for bulging is predominant, it occurs in conjunction with the pile action since the applied loads are transmitted to the surrounding soil through resistances mobilized around the perimeter and the base of the stone column. For the granular pile at the verge of bulging, not only a lateral confining stress but shear stresses act (Fig. 1a) on the cylindrical surface.

The stress conditions on the stone column of diameter $d_p (=2a)$ at the verge of failure are shown in Fig. 1a. The capacity of the column, q_v , is governed by the horizontal stress, σ_h , given by the bulging capacity of the soft soil, and by the shaft resistance, τ , (pile mechanism). Using the arching theory proposed by Handy (1985), the average vertical stress, $\sigma_{v,av}$, is obtained as

$$\sigma_{v,av} = \sigma_1 \cdot 2 \int (\sin^2 \theta_i + K_s \cdot \cos^2 \theta_i) r dr / a^2 \quad (1)$$

where σ_1 is the major principal stress, θ_i - is the inclination of the minor principal plane to the horizontal, and $K_s = \tan^2 \phi'$. θ_i is obtained from the shape of the catenary in terms of θ_s the inclination of the plane at radius, $r = a$. The angle θ_s derived from the stress conditions on the cylindrical surface. The lateral stress, σ_h , is related to the major principal stress as

$$\sigma_h = \sigma_1 \cdot (\cos^2 \theta_s + \sin^2 \theta_s) \quad (2)$$

Eqs. (1) and (2) are combined and integrated numerically to obtain the stone column capacity as a function of ϕ' and the stress ratio τ/σ_1 . Results obtained are presented and compared (Fig. 1b) with the earlier approaches and the experimental results. If τ is zero ($\tan \delta = 0$), only bulging failure is possible and Hughes and Wither's result is obtained. The stone column capacity decreases with increasing values of $\tau/\sigma_1 = \tan \delta$. For $\delta = \phi'$, the capacity reduces to about 50% of the value for pure bulging. The capacity values predicted by the combined bulging - pile mechanism appear to agree with the measured values of Bergado et al. (1991) and suggest that possibly large shear stresses are being transferred from the granular pile near its top.

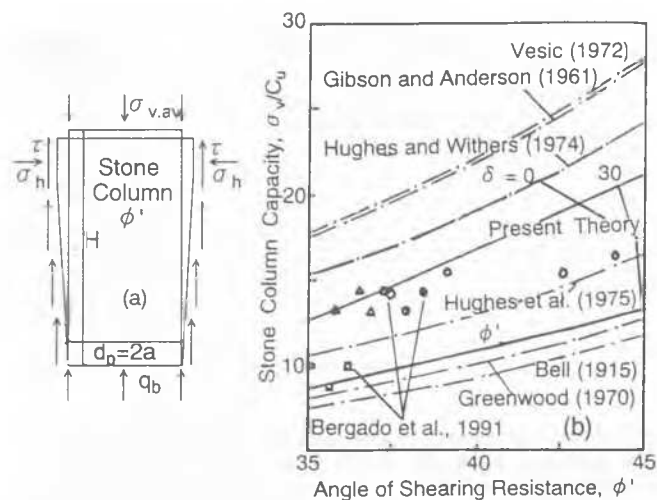


Fig. 1(a) Stresses on stone column (b) Comparison of predicted and measured values

The material used in stone columns is dense, angular gravel or sand. The vertical stress on stone column is often close to the peak strength and the material dilates. Van Impe and Madhav (1992) present an analysis (Fig. 2a) for settlement of stone column reinforced soil considering the dilation of the stone column. The reduction in settlement of the treated ground (Fig. 2b) can be significantly more even for a small percentage (0.5%) of dilation compared to the case no dilation takes place.

Stone columns are often treated as end bearing piles (Bergado et al. 1991, Van Impe and Madhav, 1992) even though the deformation modulus of the stone columns is only of the order of 20 to 50 times that of the in situ ground. By analogy with the analysis of piles (Mattes and Poulos, 1971), they should be treated as compressible piles which transfer loads through large shear stresses generated near their top end. The analysis presented by Van Impe and Madhav (1992) can easily be extended by incorporating the stress transfer through the stone column (Fig. 2c) and integrating for soil and stone column displacements.

LIQUEFACTION DAMAGE MITIGATION

The range of soils, saturated uniform sands to silts which are most susceptible to damage due to liquefaction, falls in the range of soils that can be improved by stone columns, especially by vibro-replacement (Priebe, 1989). It is reported (Mitchell and Wentz, 1991) that no damage was found from the twelve stone column improved sites subjected to the 1989 Loma Prieta earthquake. Stone columns mitigate the potential for liquefaction and damage by (i) preventing build up of high pore pressures, (ii) providing a drainage path, and (iii) increasing the stiffness of the ground by reinforcement. Loose sandy deposits densify by vibro-replacement. Seed and Booker (1975) study the drainage function of stone columns and provide design criteria in terms of number of cycles for liquefaction and number of equivalent cycles for a given earthquake magnitude. Saito et al. (1987) recommend that the

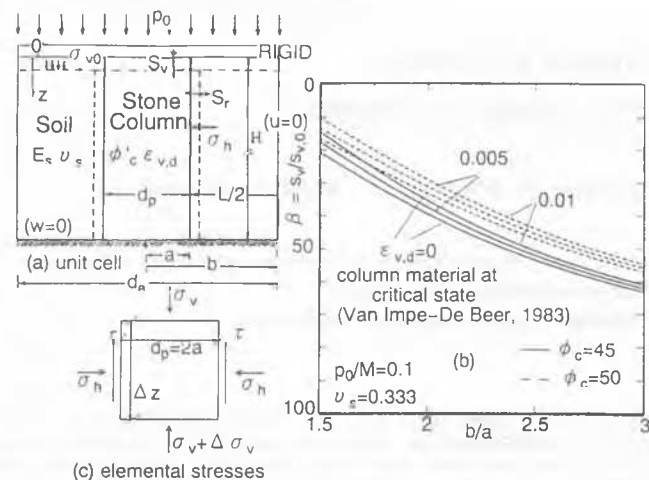


Fig. 2 Settlement Reduction Parameter (after Van Impe and Madhav, 1992)

stone size be selected to satisfy the filter criterion $20.d_{s15} < d_{c15} < 9.d_{s85}$ where d_{s15} and d_{s85} correspond to 15% and 85% finer sizes of in situ soil, and d_{c15} to the stone column material. The stiffness of the reinforcing element reduces post liquefaction ground displacements (Yasuda et al., 1992) within a distance of one to two diameters of soil close to the stone columns.

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