DOES LATERAL STRESS REALLY INFLUENCE SETTLEMENT?

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ABSTRACT: Construction innovations such as compaction grouting, the use of a reverse pitch section for installing augercast piles, and the use of beveled rammers to compact rammed aggregate piers, all emphasize the development of lateral in situ soil stress. The question posed herein is whether lateral stress in itself may reduce settlement, aside from any influences through densification or increased skin friction. Stress paths for a normally consolidated soil that is laterally stressed to the passive limit, then vertically loaded, gives a sequence of Mohr circles that indicates a shift from consolidating to near-linear-elastic behavior. The change requires and appears to depend on reversals in the directions of intergranular friction. As these reversals should occur with very little strain, they do not require that the soil be significantly compacted. Excess pore pressures that may develop should be relieved with the aggregate pier method of soil reinforcement. The reinforced soil layer should distribute stresses to the underlying soil in a manner that is similar to the action of a highway base course.

INTRODUCTION

Tapered displacement piles, pressure-injected piles, compaction grouting, the addition of a reverse pitch section to augers installing augercast pile, stone columns, and the introduction of short aggregate piers compacted by ramming (Geopier soil reinforcement), tend to increase lateral stresses in soils. The intent is to increase pile skin friction and densify the adjacent soil, but what of the influence of the lateral stress itself? Does lateral stress influence foundation settlement, and if so, how? This possibility was suggested when settlement measurements of buildings on soils reinforced with short aggregate piers were much less than anticipated from conventional consolidation theory (Lawton et al. 1994).

REVIEW

K_a Shear Envelopes

Rankine theory indicates that the vertical-to-lateral effective stress ratio that will cause shear failure of soil under a horizontal surface is

$$K_a = \frac{1 - \sin \phi'}{1 + \sin \phi'} \tag{1}$$

where K_a = coefficient of active earth pressure; and ϕ' = angle of internal friction on an effective stress basis. This relationship defines linear failure envelopes that are inclined $\pm\phi'$ from horizontal (Fig. 1).

K_0 Consolidation Envelopes

A constant stress ratio realized during nascent consolidation describes envelopes similar to shear envelopes but lower. By definition in a normally consolidated soil, that is, a soil that has consolidated to equilibrium under the existing weight of overburden

$$K_0 = \frac{\sigma'_h}{\sigma'_v} \tag{2}$$

where σ'_h and σ'_v = horizontal and vertical effective stresses, respectively. A common estimator for K_0 is the Jáky equation

$$K_0 = 1 - \sin \phi' \tag{3}$$

Eq. (3) may be used to define consolidation envelopes that are inclined at $\pm\beta'$ from horizontal (Fig. 1).

The slope of the consolidation envelope may be determined in the same manner as the slope of the shear envelope presented in most soil mechanics textbooks

$$\sin \beta' = \frac{\frac{1}{2}(\sigma'_v - \sigma'_h)}{\frac{1}{2}(\sigma'_v + \sigma'_h)} \tag{4a}$$

$$\sin \beta' = \frac{\sigma'_v - \sigma'_h}{\sigma'_v + \sigma'_h} \tag{4b}$$

Combining (2)–(4) gives

$$\beta' = \sin^{-1}\left\{\frac{\sin \phi'}{2 - \sin \phi'}\right\} \tag{5}$$

As long as the respective *K*s are constant, both the shear and consolidation envelopes extrapolate through the origin regardless of whether the soil is granular or cohesive (Lambe and Whitman 1969). Thus, the analysis presented below should apply equally to fine-grained and to granular soils. Some representative solutions for (5) are as follows, [ϕ' (deg), β' (deg)]: [0, 0]; [5, 2.61]; [10, 5.46]; [15, 8.55]; [20, 11.9]; [30, 15.5]; and [40, 19.5].

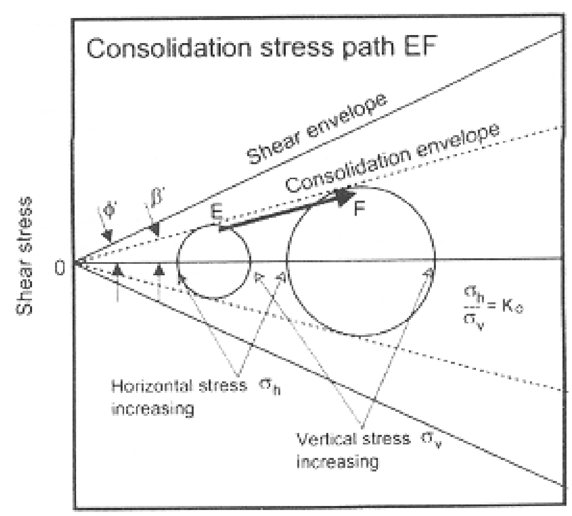

FIG. 1. Mohr Circle Sequence and Stress Path *EF* during Normal Consolidation

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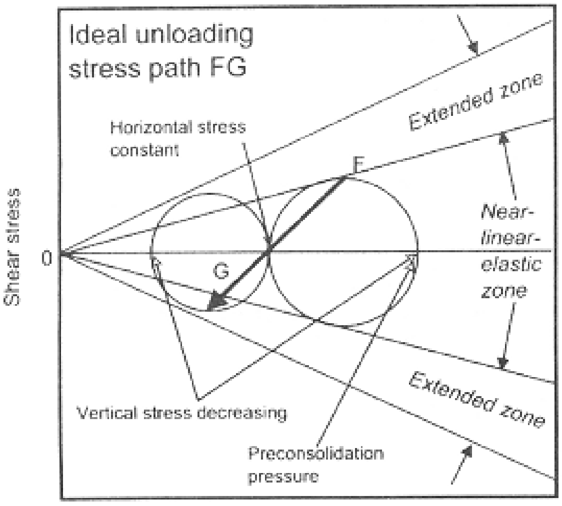

FIG. 2. Mohr Circle Sequence and Stress Path *FG* as Reductions in Vertical Stress Create Overconsolidated Soil

Stress Path during Consolidation

An increase in vertical stress that causes a soil to consolidate gives a proportionate increase in horizontal stress so that the Mohr circle remains tangent to the consolidation envelope, according to stress path *EF* in Fig. 1.

Stress Paths during Unloading and Reloading

A reduction in vertical stress leaves the horizontal stress mostly intact (Mayne and Kulhawy 1982), and therefore approximately follows stress path *FG* in Fig. 2. On reloading, the path approximately reverses along path *GF*. Because the soil behavior during unloading and reloading up to the preconsolidation pressure is near-linear-elastic, the stress zone enclosed by the consolidation envelopes will be referred to as the near-linear-elastic zone. Because unloading may extend the stress path past the consolidation envelope into an area between the consolidation and shear envelopes, this is referred to as the extended near-linear-elastic zone, or simply the extended zone.

CONSOLIDATING VERSUS NEAR-LINEAR-ELASTIC SOIL BEHAVIOR

Ideal elastic behavior is seldom realized in soils, probably because of localized slippage from stress concentrations within a soil mass. Nevertheless, the physical significance of consolidation compared with near-linear-elastic behavior is that during consolidation virtually all soil grains become irreversibly rearranged by slipping and rolling over one another; whereas during near-linear-elastic expansion or recompression, they do not. Thus during consolidation, instead of strain being approximately proportional to stress as in the elastic case, strain is more nearly proportional to the logarithm of stress as the soil densifies and the modulus increases. The increase is permanent as long as the soil structure remains intact.

Near-Linear-Elastic Behavior and Foundation Design

Near-linear-elastic response is frequently relied upon to minimize settlement in conservative foundation design by making distributed foundation pressures equal to or less than preconsolidation pressures at all depths. This procedure is particularly appropriate for sensitive clays that must be guarded against loss of strength from localized incipient shearing.

HIGH LATERAL STRESS AS NATURAL SOIL CONDITION

As previously mentioned and as shown in Fig. 2, overconsolidation leaves horizontal stress close to a level that is consistent with the preconsolidation pressure. Field tests made during development of the K_0 stepped blade showed that most soils are at least slightly overconsolidated (Handy et al. 1990) as a consequence of unloading through erosion, buoyancy from a rise in the level of the ground-water table, glacial preloading, and dessication shrinkage of expansive clays. Even though expansive clays are overconsolidated from within, attributable to very high negative pore pressures developed upon drying, they can exhibit lateral stresses up to the passive limit from development of vertical shrinkage cracks by crack filling and reexpansion.

Overconsolidation Ratio Not Constant with Depth

The overconsolidation ratio (OCR) represents the ratio between preconsolidation and overburden pressures, and in an overconsolidated soil deposit varies with depth, becoming infinite at the ground surface. Thus the OCR, while appropriate for describing the degree of overconsolidation of individual soil samples, does not describe the degree of overconsolidation of a soil deposit unless a depth or overburden pressure are specified, and an alternative measure has been suggested.

MECHANICALLY INDUCED HIGH LATERAL STRESSES

Vertical Compaction

Mechanical compaction in effect overconsolidates soil so future loading will be in the near-linear-elastic zone.

Horizontal Stress from Compaction Grouting

Lateral stresses developed during compaction grouting equal grout pressures at the points of injection, which normally are less than the overburden pressure to prevent uplift or venting. That being the case, compaction grouting may be expected to develop a maximum K_0 of 1.0.

Horizontal Stress near Displacement Pile

High lateral stresses develop close to driven piles (Handy et al. 1990). A simultaneous increase in radial stress and reduction in tangential stress encourages shearing and development of a passive condition.

Horizontal Stress near Rammed Aggregate Piers

Lateral stresses indicative of passive conditions have been measured close to and between rammed aggregate piers. The total energy input is comparable to that from deep dynamic compaction by repeatedly lifting and dropping a heavy weight, but is evenly distributed through the length of the piers instead of being applied at the ground surface (Handy et al. 1999). Pullout measurements of the piers show a near-linear-elastic response that was an early clue that there might be a fundamental change in the soil behavior.

FOUNDATION SETTLEMENT AND LATERAL STRESS

Stress Path to Reduce Settlement

Lateral stress imposed on a normally consolidated soil gives stress path *AB* in Fig. 3, and can proceed as high as the passive limit. Subsequent foundation loading then follows a stress path *BC*, which is in the near-linear-elastic zone. At *C* the Mohr circle intersects the consolidation envelope, ending the expanded near-linear-elastic response and initiating consolidation. Foundation loads on a normally consolidated soil confined by high lateral stress therefore should elicit a near-linear-elastic response instead of immediately initiating consolidation.

The theoretical maximum vertical stress before consolidation can begin is obtained from definitions of $K_p = H_2/V_1$ and $K_0 = H_2/V_2$ (Fig. 3), where H and V represent horizontal and vertical stresses and the subscripts denote before-and-after loading. Solving each for H_2 and equating gives

$$\frac{V_2}{V_1} = \frac{K_p}{K_0} \tag{6}$$

where V_2 = vertical effective stress required for consolidation; V_1 is in situ vertical effective stress or overburden pressure; and K_p = passive coefficient, which is the reciprocal of K_a [(1)]. The ratio V_2/V_1 may be defined as a reinforcement factor K_r that represents the maximum benefit attainable with a normally consolidated soil

$$K_r = \frac{1 + \sin \varphi'}{(1 - \sin \varphi')^2} \tag{7}$$

A high initial lateral stress gives a "head start" deferring consolidation to a higher stress level, but the relationships still apply. For example, Saye (1984) reported reduced settlements of grain elevators supported on a desiccated expansive clay crust. Some representative solutions for (7) for a normally consolidated soil are as follows, [ϕ' (deg), K_r]: [0, 0]; [5, 1.3]; [10, 1.7]; [15, 2.3]; [20, 3.1]; [25, 4.3]; [30, 6.0]; and [40, 12.9]. Thus, for the normally consolidated soil of Fig. 3 with a friction angle of 25° subjected to passive lateral stress, the overburden pressure at any depth may be exceeded by a factor of 4.3 before consolidation can begin. Without the additional lateral stress, consolidation settlement would initiate as soon as an additional load is applied.

A similar expression including soil cohesion may be developed by adding the intrinsic stress $a' = c' \cot \varphi'$ to the applied normal stresses, where c' represents the cohesion on an effective stress basis. However, soils stressed and remolded to the passive limit temporarily have little cohesion, so the cohesion that develops through time may be regarded as giving an additional margin for safety.

Compaction Grouting

In compaction grouting a stiff, nonpenetrating grout is used in order to displace instead of permeate the soil. Because as previously mentioned the maximum K to avoid uplift is 1.0, stress path AB in Fig. 3 stops at the horizontal axis, and the center circle in Fig. 3 reduces to a point. The maximum reinforcement ratio becomes

$$K_g = (1 - \sin \varphi')^{-1} \tag{8}$$

Thus if $\varphi' = 25°$, the maximum reinforcement factor is 1.7, compared with 4.3 if the lateral stress were to be increased to the passive limit.

Influence on e-log p Relationship

As a high horizontal stress must defer consolidation to a higher value of vertical stress, the preconsolidation pressure must be displaced to the right on a plot of void ratio versus logarithm of pressure, similar to the action of a weak cementation. This behavior, which appears to previously have been overlooked, will not be revealed in conventional laboratory odometer or triaxial testing that does not apply high lateral stress before vertical loading.

Simulated Base Course

A stress-reinforced surficial layer that behaves near-linear-elastically under load is analogous to a highway base course that behaves near-linear-elastically to distribute loads to underlying less competent soils.

If Lateral Stress Is Relieved

What if the lateral stress is relieved at some future time, as by excavation close to a stress-reinforced layer? The same question, of course, applies to friction pile: If lateral stress is somehow relieved, does that reduce the friction? The most obvious answer is not to relieve lateral stress, particularly in the early life of a foundation. Gains in soil strength with time, even of sandy soils (Schmertmann, 1970), tend to reduce this danger.

Undrained Conditions

In an ideal undrained situation with a friction angle of zero and the soil at incipient failure, the analogous chain of Mohr circles gives

$$K_r = 1 + \frac{4c}{V_1} \tag{9}$$

where c = cohesion on a total stress basis; V_1 = initial vertical stress; and the limiting condition is not consolidation but shear failure. Thus it appears that settlement of structures on soft, saturated clays may be reduced by lateral stressing.

KEY ROLE OF FRICTION REVERSAL

The conventional notation for shear directions is shown in Fig. 3, where data plotting above the horizontal axis denotes counterclockwise shear. A simple model illustrating this is shown in Fig. 4, where the top diagram shows shear directions and contact friction in a normally consolidated soil. Here, friction acts in support of the higher vertical load, and supplies a reason for horizontal stress being lower than vertical stress in a normally consolidated particulate medium. With the application of horizontal stress as the stress path crosses the X-axis, shear directions are reversed, and as shown in the middle diagram contact friction acts to oppose the increased horizontal stress. In the bottom diagram when a foundation load is applied and the stress path again crosses the X-axis, shear direc-

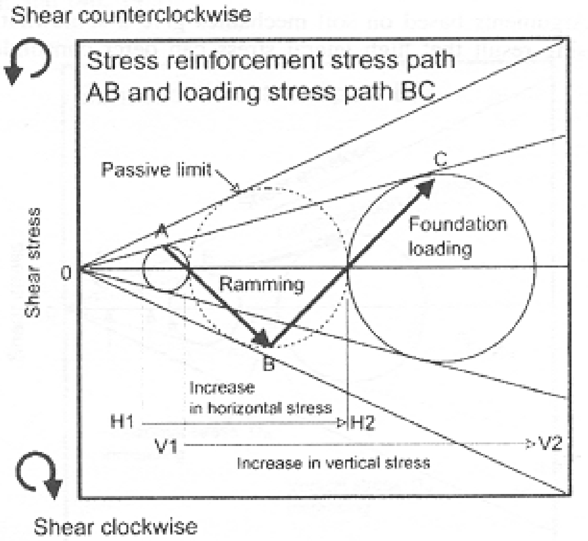

FIG. 3. Increasing Horizontal Stress on Normally Consolidated Soil (Stress Path AB) Increases Consolidation Threshold Stress from V_1 to V_2 (Stress Path BC)

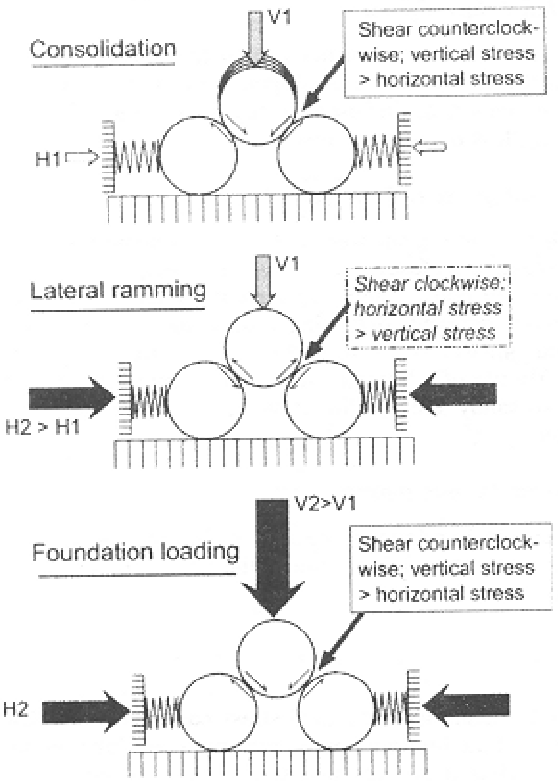

FIG. 4. Friction Reversals to Explain Increased Allowable Vertical Stress V_2 before Consolidation Can Initiate

tions again are reversed, and, as in the case of the normally consolidated soil, consolidation can begin only when the vertical stress is sufficient to overcome the frictional resistance.

Significantly, friction reversals can occur with very little strain and consequent development of excess pore pressure. An analogy is a brick on a board: As the board is tilted one way or the other, the direction of friction between the brick and the board reverses but the brick does not move. This suggests that compaction is not required in order to reverse frictional restraints, and without compaction excess pore water pressures should be negligible. Excess pore pressures that do develop may be relieved by air voids in aggregate piers or columns.

CONCLUSION

Arguments based on soil mechanics give a somewhat surprising result that high lateral stress can defer consolidation settlement to a substantially higher foundation load, without any influence from densification of the soil and without necessarily increasing the pore water pressure. A stress-reinforced layer should exhibit near-linear-elastic behavior analogous to that of a highway base course. It should be emphasized that the reinforcement factor is fully developed only in soil that has been horizontally stressed to the passive limit, as where the reinforcing elements are closely spaced in lines or in groups.

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NOTATION

The following symbols are used in this paper:

- c, c' = cohesion on total stress and effective stress basis, respectively;
- H_1 = horizontal effective stress in normally consolidated soil;
- H_2 = enhanced horizontal effective stress;
- K_a = coefficient of active earth pressure;
- K_p = coefficient of passive earth pressure;
- K_r = reinforcement factor or ratio of V_2/V_1;
- K_0 = coefficient of earth pressures at rest;
- V_1 = effective overburden stress;
- V_2 = vertical effective stress required to initiate consolidation in stress-reinforced soil;
- β' = slope of consolidation envelope;
- ϕ' = angle of internal friction on effective stress basis and slope of failure envelope;
- σ'_h = horizontal effective stress; and
- σ'_v = vertical effective stress.