Shear modulus of rockfill from lateral pile load test

Module de cisaillement d'enrochement à partir d'essais de charge latérale sur les pieux

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SYNOPSIS: A procedure is outlined for backfiguring the variation of secant shear modulus with strain-amplitude in rockfill, from the results of a lateral pile load test. The test involves a circular concrete pile, 0.75 m in diameter and 32 m in length, embedded in a layered soil profile, the top 5 m of which is a recently-placed rockfill. The results of the back analysis, plotted in the form of modulus-versus-strain are in very good qualitative and quantitative accord with (i) lab test results on large triaxial samples and (ii) backfigured results from the recorded seismic response of rockfill dams, developed by Seed & coworkers.

1 INTRODUCTION

Full-scale pile load tests are performed in the field in order to verify that the pile can transmit the design loads with an adequate factor of safety against failure. However, it is possible to take better advantage of such tests and extract valuable information on the behavior of the surrounding soils. To this end, a back analysis of the results must be performed using a suitable theory and modeling the particular pile-soil system.

Lateral pile load tests, although not as popular as the axial tests, can be especially useful in this respect, for two main reasons : First, lateral loading induces deformations that are felt only within a shallow depth (a few pile diameters) from the ground surface. Hence, it is only the top one of two soil layers that resist the load, and it is a much easier and more reliable task to recover their properties from the measured response of the pile than it is to obtain the properties of all the soil layers that are usually affected with axial loading. Second, a complete lateral pile load test produces a nonlinear force-displacement response, from which information can be extracted for the nonlinear stress-strain behavior of the affected soils (e.g. Poulos 1988).

The pile load test utilized in this article was performed in conjunction with the foundation design for one of the pylons of a cable-stayed bridge. A very interesting aspect of this test was the presence of a recently-placed layer of rockfill on top of a dense/stiff natural soil deposit. The backfigured information for the shearing behavior of this rockfill enriches the scarce data presently available in the published literature for such a material.

2 DESCRIPTION OF PILE AND ROCKFILL

The tested pile was a reinforced-concrete cast-in-place 32 m long pile having a nominal diameter of 0.70 m. However, since casing was provided only down to a depth of 15 m, and this casing was removed during casting, the actual diameter varied from about 0.75 m in the upper half to 0.67 m in the lower half.

The top 5 m of the soil profile is fill material, placed in order to create an artificial island on which the main pylon of the cable-stayed Evripos bridge will be founded. The upper half of this fill is quarry rockfill, while the lower half consists of slightly cemented silty sand-and-gravel. The underlying soil comprises a very heterogeneous 15 m thick layer of clayey sand with gravel and rock fragments; its presence prompted the use of piles as the proper foundation scheme. Fig. 1 depicts the soil profile of the test site.

The rockfill is of limestone origin, having angular and subangular grains; its grain-size distribution is portrayed in Fig. 2. Notice that the effective diameter is D10 = 50 mm, while the main diameter is D50 = 160 mm. The relative density Dr is estimated to be about 80%.

The mechanical behavior in shear of this rockfill is expected to be nonlinear and inelastic, even for relatively small shear strains (see Marsal 1973). Due to the small confining pressures prevailing near the ground surface, one would also expect a dilatant behavior. Nonetheless, the methods often employed in practice for estimating lateral pile deformations adopt linear models for soil response. Such an approximation would be realistic for monotonic loading, only if the "effective" (secant) shear modulus is considered a decreasing function of strain amplitude. The term "equivalent linear" model has been used to describe such an approximation.

This model is also adopted herein, in which case the secant shear modulus, G, of the rockfill is a function of only two variables : the amplitude of shear strain, γ_c, and the mean normal ("confining") stress, $\bar{\sigma}_o = (\bar{\sigma}_{vo}+2\bar{\sigma}_{ho})/3$. Seed et al. (1986) have proposed that

$$G = 1000\ K_2(D_r,\gamma_c)\ \sqrt{\bar{\sigma}_o} \qquad (1)$$

in which the coefficient K_2 increases with relative density Dr and decreases with strain amplitude γ_c.

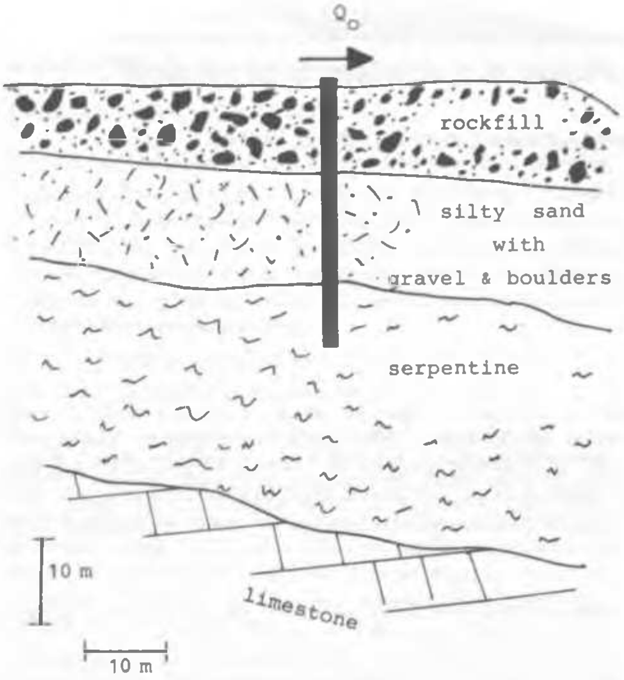

Figure 1. Soil profile and tested pile.

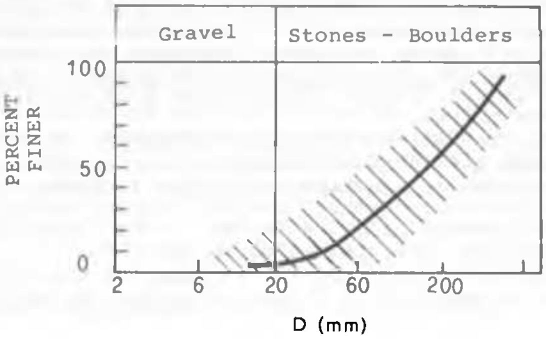

Figure 2. Grain-size distribution curve of the top rockfill layer.

3 BACK ANALYSIS OF LATERAL LOAD TEST

A horizontal force at the head of the pile reached a maximum value $Q_o = 0.70$ MN and produced the force-displacement curve depicted in Fig. 3. The observed yielding is solely due to the aforementioned decrease of rockfill G with increasing γ.

The pile deflection profiles, recorded with an inclinometer, are also portrayed in Fig. 3 for three levels of lateral load. As anticipated only the top three or four meters of pile "see" the load. Evidently, resistance to pile movement comes mainly from the rockfill. One can therefore model the soil profile as a statum with a parabolically increasing Young's modulus with depth. From Fig. 1, assuming reasonable values of Poisson's ratio and of the coefficient of lateral earth pressure at rest, this latter modulus takes the form :

$$E(z) \fallingdotseq 11000\, K_2 \sqrt{z} \tag{2}$$

Closed form analytical solutions for a free-head pile embedded in soil obeying Eqn 2 have been presented by, among others, Gazetas (1983). Thus, the load-deflection ratio may be expressed as

$$\frac{Q_o}{y_o} \fallingdotseq 0.35\, d\, E_s\, (E_p/E_s)^{0.30} \tag{3}$$

where : E_p = the Young's modulus of pile, d = its diameter, and E_s = the modulus of soil at a depth equal to one diameter, $E_s = 9530\ K_2$. Substituting these values, Eqn 3 becomes

$$\frac{Q_o}{y_o} \fallingdotseq 28000\, K_2^{0.70} \tag{4}$$

For each level of loading the actual ratio Q_o/y_o is first obtained from Fig. 3 and then Eqn 4 is utilized to obtain the corresponding value of K_2.

The corresponding value of the <u>average effective</u> shear strain can be estimated from the simplified relationship

$$\gamma_c \fallingdotseq \frac{2}{3}\ \gamma(z=0) \fallingdotseq \frac{2}{3}\ \frac{1+\nu}{2.5d}\ y_o \tag{5}$$

in which y_o is the pile deflection at the top (z=0). Thus, for each level of loading, one computes γ_c from Eqn 5, after y_o has been read from Fig. 3. Hence, it is possible to estimate the relationship $K_2 = K_2(\gamma_c)$ by repeated use of Eqns 4 & 5 and the results of the lateral load test (Fig. 3).

4 RESULTS AND DISCUSSION

The backfigured data points K_2 and $_c$ are depicted in Fig. 4. Also shown on this figure are the curves recently proposed by Seed et al (1986), on the basis of laboratory and field data of a completely different nature than that of the pile test data utilized herein. Specifically, Seed et al made use of (i) large-cell triaxial test results on gravel and rockfill material and (ii) recorded earthquake motions on the crest and at the base of tall rockfill dams.

The agreement between the results derived in this article and those of Seed is very encouraging. Notice <u>the rate of decline</u> of the effective Shear Modulus G with increasing level of effective strain is practically identical between the two sets of data. This remarkable outcome suggests that the proposed back analysis procedure is indeed reasonable. It should also be noted that largest "average effective" strain of pile load test is of the order of 2% - which is an order of magnitude greater than the largest strain of the Seed et al data. Hence, valuable information is obtained from the pile tests.

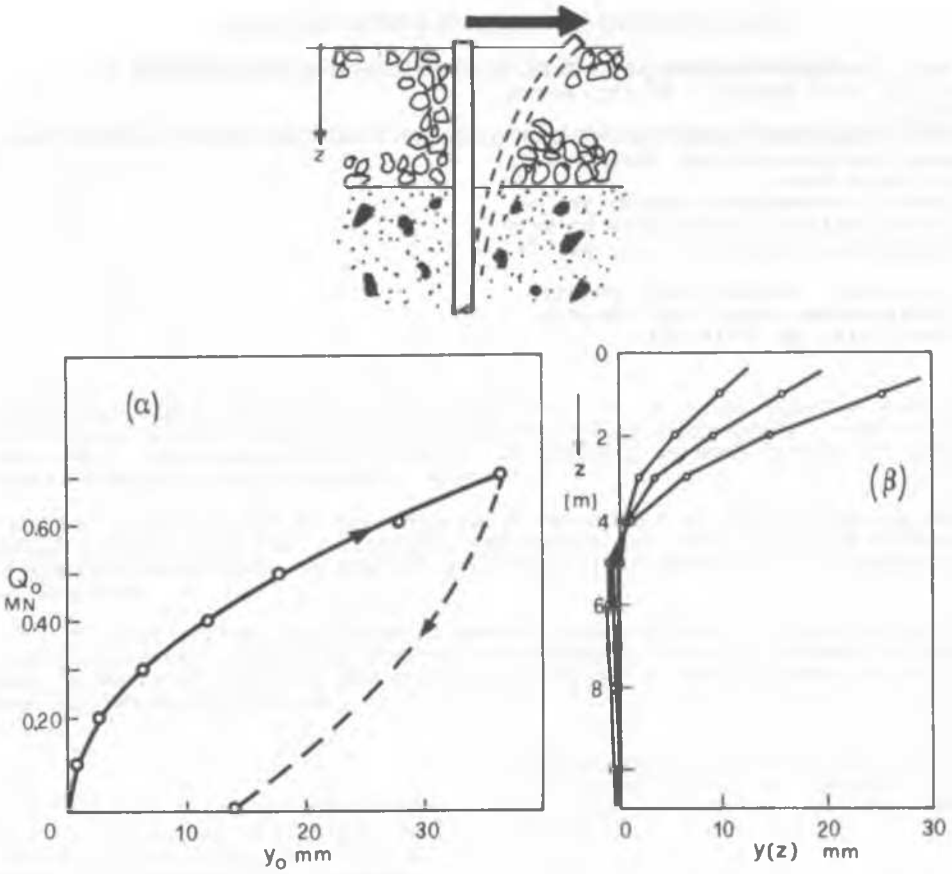

Figure 3. Results of pile load test: (α) Lateral force-displacement relationship; (β) Profiles of pile deflection at different levels of the applied force.

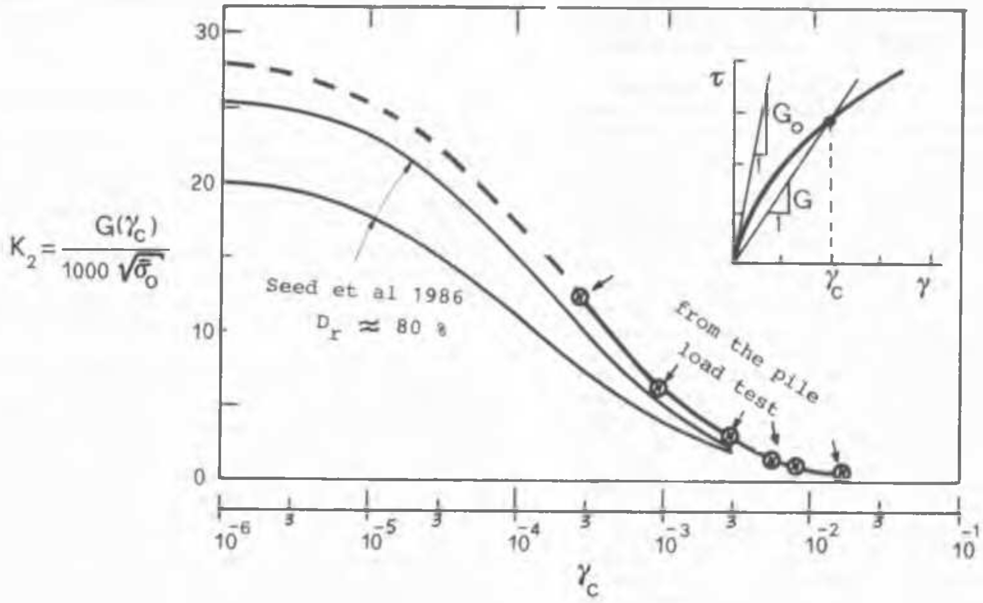

Figure 4. Decay of the modulus coefficient K_2 (in units of $(kPa)^{1/2}$) with increasing shear strain amplitude. The results backfigured from the pile test are in accord with Seed's data.

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