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Paper No. 1017. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

EFFECTS OF EARTH SLOPE CHARACTERISTICS ON DISPLACEMENT BASED SEISMIC DESIGN

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ABSTRACT

The design of earth slopes subjected to seismic loads can be effectively based on the analysis of potential permanent displacements (Simonelli, 1993). The displacement of a slope strongly depends on the characteristics of the exciting accelerometric waveform (Simonelli and Viggiani, 1995); hence it is fundamental to reliably define the seismic motion expected at the site. The behaviour of the slope obviously depends on the mechanical soil properties, on the pore pressure distribution and on the geometrical configuration too. In this paper the effects of these factors on the slope response have been evaluated. The well-known Newmark model (1965) has been utilized, which is very effective to study sliding phenomena induced by the inertial forces due to seismic loading (Whitman, 1993). The reference input motion of Irpinia region in Southern Italy has been assumed as exciting function (Simonelli and Viggiani, 1995). The results of the analyses have been synthetised in simple design charts, which correlate the expected maximum permanent displacement to soil-slope characteristics as soil friction angle and slope inclination. In particular the typical cases of dry and saturated cohesionless soils have been compared; then a more general design approach has been defined, which can be applied to any soil-slope configuration whose critical acceleration value has been preliminarly determined.

KEYWORDS

Earth slope stability; displacement analysis; seismic design; design charts.

INTRODUCTION

The values of earthquake caused permanent displacement are increasingly adopted as basic parameters in recent slope seismic design criteria. Predictions of induced displacements can be performed by means of different approaches, which range from analyses based on the simple model of a block sliding on a plane surface (Newmark, 1965), to the more recent and sophisticated finite element analyses, which often involve quite complex constitutive models for the soils. The choice of the analysis method should be performed taking account of the kind of phenomenon which is being studied, and of the accuracy of the solution required for the particular problem (Wroth and Houlsby, 1985).

The well-known Newmark model is very effective to analyse sliding phenomena caused by yielding due to overstressing by inertial forces induced during the shaking (Whitman, 1993). Significant applications based

Table 1. Irpinia main accelerometric recordings: sites and corrected data characteristics.

IRPINIA	Comp.	T (s)	Amax (cm/s²)	Vmax (cm/s)	Ia (cm/s)	fo (Hz)
BAGNOLI IRPINO	NS	79.1	135.4	20.2	36.4	0.9
23/11/1980 – 18 34' 52"	WE	79.1	176.6	29.3	44.7	0.9
BRIENZA	NS	78.8	209.0	12.5	54.2	5.0
23/11/1980 – 18 34' 52"	WE	78.8	172.7	9.4	45.3	4.0
CALITRI	NS	86.1	151.1	24.8	105.9	1.1
23/11/1980 – 18 34' 52"	WE	86.1	176.6	26.4	137.2	1.0
MERCATO S.SEVERINO	NS	79.9	105.0	7.2	32.1	1.5
23/11/1980 – 18 34' 52"	WE	79.8	138.3	13.3	53.3	1.2
STURNO	NS	70.7	218.8	31.2	126.9	2.5
23/11/1980 – 18 34' 52"	WE	70.7	310.0	50.5	143.4	0.4

T : time duration; Ia : Arias intensity; fo : predominant frequency

on this model have been performed, utilizing, as input motion, sets of "homogeneous" accelerometric data, recorded all over the world. The results have been analysed to define upper bound limits to seismic displacements or to assess the probability of exceedance of lower displacement values (Ambraseys and Menu, 1988). The case of indefinite slope and cohesionless soil has been most frequently studied; the effect of excess pore-pressure generated during the earthquake has been taken into account by Sarma (1975). The response of the slope has shown to be strongly dependent on the characteristics of the exciting accelerometric waveform, as maximum acceleration, maximum velocity, frequency and energy content, duration (Sarma and Yang,1987, Simonelli and Viggiani, 1995). Hence it is fundamental to define a proper set of accelerometric time-histories, which can significantly represent the seismic motion expected at the site.

A slope displacement analysis has been performed by Simonelli (1993) on the basis of a wide set of accelerometric data recorded during the 11.23.1980 Irpinia earthquake in Southern Italy, which probably is the heaviest event the region ever suffered. A Design Chart was drawn, for indefinite slope and dry cohesionless soil, which correlates the permanent displacement to the site maximum acceleration and to soil-slope characteristics. The effect of the different parameters of the recorded accelerometric waveforms was accounted for by defining the correlation function between the maximum displacement and the critical acceleration ratio (i.e. the critical acceleration of the slope over the maximum value of the accelerogram) according to Ambraseys and Menu (1988). The upper bound curve for the computed displacements was utilized; nevertheless the results evidentiated the overconservativeness of the traditional pseudo-static design of the present Code.

In this study displacement analyses for different mechanical soil properties, pore pressure distributions and geometrical configurations are performed utilizing the Newmark model, and their effects on slope response are evaluated. The accelerometric data of Irpinia region, properly corrected to eliminate the noise effects (Simonelli and Viggiani, 1995), are assumed as reference input motion. The results will be synthetised in simple design charts, with the aim to correlate the maximum permanent displacement to soil-slope characteristics.

DISPLACEMENT ANALYSIS

Reference input motion

Irpina accelerometric data have been adopted as reference input motion. The detailed analysis of the seismic recordings and illustrations of the corrected waveforms are presented by Simonelli and Viggiani (1995). Here the main characteristics of the strongest analysed accelerograms are reported in Table 1.

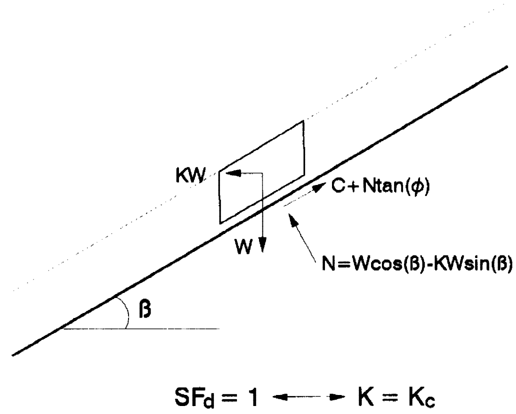

Fig. 1. Rigid block sliding on a plane surface and critical acceleration coefficient K_c.

Soil-slope configurations

Critical acceleration coefficient. The behaviour of a slope under seismic actions can be significantly related to the acceleration value $K_c * g$ (where g is gravity), whose correspondent inertial forces would induce the limit equilibrium condition. With reference to the adopted model represented in Fig.1 (where the direction of the acceleration is horizontal), the critical acceleration, hence its coefficient K_c, can be easily defined imposing the dynamic safety factor SF_d equal to 1. A significant expression of K_c as a function of the static safety factor SF is

$$K_c = (SF - 1) \frac{\tan(\beta)}{1 + \tan(\phi') \cdot \tan(\beta)} \qquad (1)$$

where ϕ' is the soil friction angle. Obviously the more the slope safety factor is greater than one, the more the K_c value increases; moreover it significantly depends on the inclination β of the sliding surface. The three soil-slope configurations, which will be object of the displacement analysis, are examined hereafter.

Case A: indefinite slope and dry cohesionless soil. In this case (see Fig.2a) it has been found that the critical acceleration coefficient simplifies as follows (Simonelli, 1993)

$$Kc = \tan(\phi' - \beta) \qquad (2)$$

hence it is just function of the difference between the friction angle ϕ' and the slope inclination β, and not of their single values.

Case B: indefinite slope and saturated cohesionless soil ($\Delta u=0$). In this case (see Fig.4a, where Δu is the excess pore pressure induced by the dynamic excitation), the equation for the critical acceleration coefficient becomes

$$K_c = [\frac{\gamma'}{\gamma_{SAT}} \frac{\tan(\phi')}{\tan(\beta)} - 1] \frac{\tan(\beta)}{1 + \tan(\phi') \cdot \tan(\beta)} \qquad (3)$$

hence K_c depends on the single values of ϕ and β and on the ratio between the submerged and the total unit weights of the soil (γ' and γ_{SAT}).

Case C: complex soil-slope configuration. This case (see Fig.6a) regards generic configurations of soil strength characteristics (ϕ' and cohesion c'), of pore pressure distribution (u and Δu), of slope geometry and of external loads, if any. Here a simple expression for K_c cannot be utilized; the critical acceleration coefficient has to be determined by means of a back analysis of the actual soil-slope configuration, imposing $SF_d=1$.

Equation of the motion

The slope sliding phenomenon starts every time the exciting acceleration exceeds the critical acceleration of the slope ($K_c * g$), and will stop some time after, as the relative velocity along the sliding surface returns to zero. Hence the final relative displacement depends on both the critical acceleration and the exciting accelerometric time-history. The differential equation of the motion down-slope is

$$\ddot{U}(t) = \frac{\cos(\phi' - \beta)}{\cos\phi'} g \cdot [K(t) - K_c] \tag{4}$$

where Ü(t) is the relative acceleration along the sliding surface and K(t)*g is the horizontal acceleration time-history. This equation is valid for any soil-slope configuration, even for the case in which the sliding surface is not plane, provided that the direction β of the relative motion can be defined.

DISPLACEMENT RESULTS AND DESIGN CHARTS

Displacement results

For each of the soil-slope configurations previously illustrated, displacements have been computed by the integration of equation (4), utilizing 28 accelerometric time histories as exciting motion. The results have been elaborated to find out the correlation function between the maximum permanent displacement and the critical acceleration coefficient, for each examined case. On the basis of such functions, Design Charts have been drawn, which try to simply correlate the allowable displacement to the maximum acceleration expected at the site and to the basic characteristics of the soil and the slope.

Design Charts

Case A: indefinite slope and dry cohesionless soil. In this case, substituting formula (2) for K_c in the equation of motion (4), it clearly appears that the relative accelerations, hence velocities and displacements, essentially depend on the difference between the friction angle ϕ' and the slope inclination β, being the influence of the term (1/cosϕ') negligible for the usual range of the friction angle value. Displacements have been computed for assigned values of ϕ' and β. As a matter of fact, the upper bound curves of displacement vs. the critical acceleration ratio obtained for different ϕ' values are very close, so that a unique upper bound correlation function has been adopted, as shown in Fig.2b (where K_m is A_{max}/g).

On the basis of the correlation function, a simple but effective Design Chart has been drawn (Fig.3), which correlates the maximum acceleration expected at the site with the difference (ϕ'-β) for constant displacement values; hence, for a given site (A_{max}) and a defined allowable displacement (D), the slope (ϕ'-β) can be designed immediately. In the chart a dotted zone is evidentiated, where the critical acceleration of the slope is greater than the maximum acceleration of the input motion expected at the site, and no displacement can be induced.

Case B: indefinite slope and saturated cohesionless soil ($\Delta u=0$). In this case equation (4) has been integrated, substituting K_c from equation (3) and assuming the ratio γ'/γ_{SAT} equal to 0.5. Displacements have been computed for assigned values of friction angle ϕ' and slope inclination β. The results show that they

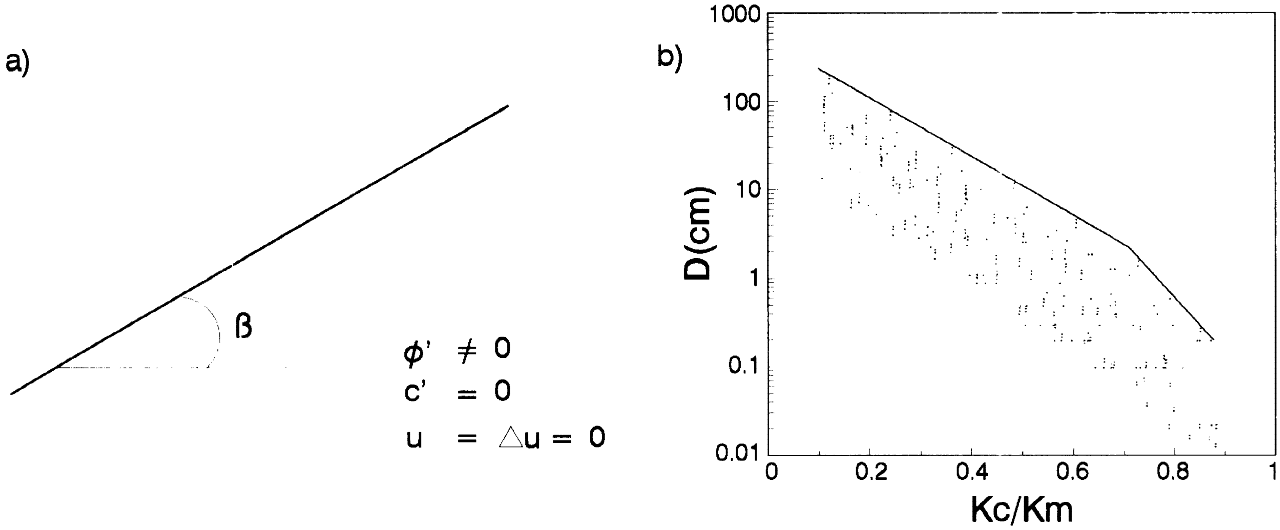

Fig. 2. a) Scheme of soil-slope configuration (case A)
b) Permanent displacement D vs. critical acceleration ratio (K_c/K_m) and upper bound lines

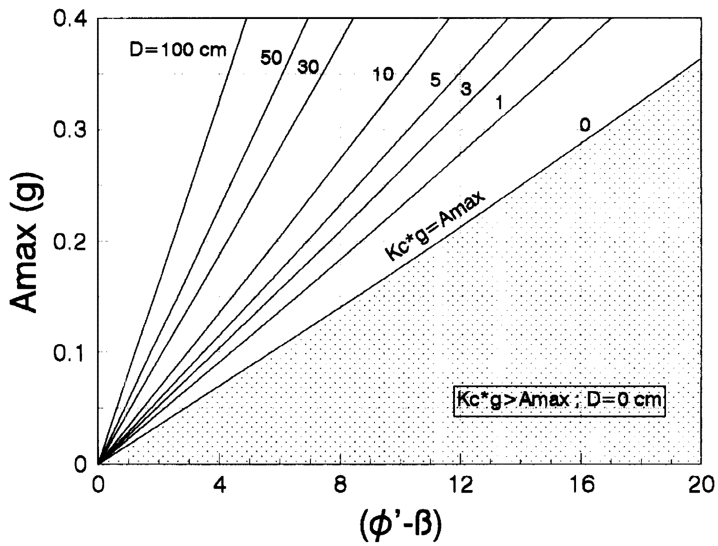

Fig. 3. Design Chart (case A): slope (ϕ'-β) vs. site A_{max} for given displacement D

obviously depend on the single values of ϕ' and β; in particular, for given (ϕ'-β) value, the displacement increases with the value of ϕ' (or β). Nevertheless, the correlation function between maximum displacement D and K_c/K_m, obtained for different ϕ' values, are quite similar; as a matter of fact, the displacements computed by the integration of equation (4), for given K_c values are scarcely influenced by the term [cos(ϕ'-β)/cosϕ']. Hence a unique upper bound correlation function has been adopted, as shown in Fig.4b.

On the basis of the correlation function, and for given values of the friction angle ϕ', it is possible to correlate the maximum acceleration A_{max} of the site with the slope inclination β. The Design Charts for ϕ' equal to 30°, 35°, 40° and 45° are plotted in Fig.5. The utilization of the chart is obvious; here the zone where D=0 is in the lower left-hand part; moreover it is worthwhile to notice that displacement curves lie on the left of the maximum value β the slope can have (for static safety factor SF=1).

Case C: complex soil-slope configuration. Here the configuration is identified by the friction angle ϕ', the direction of the relative motion β and the critical acceleration coefficient K_c, and no relation between K_c and

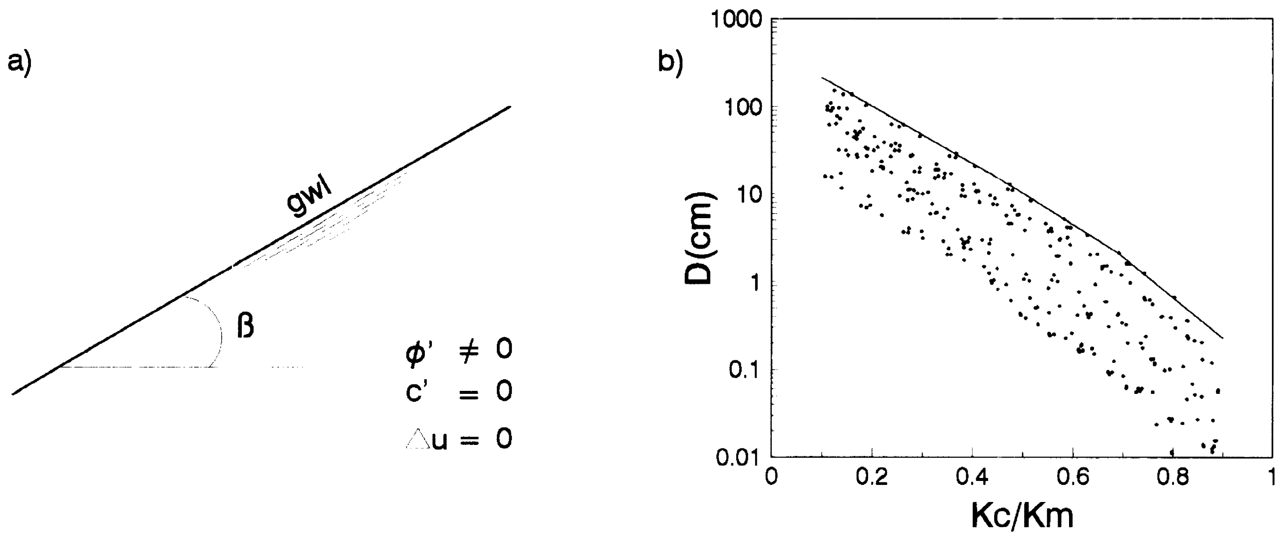

Fig. 4. a) Scheme of soil-slope configuration (case B)
b) Permanent displacement D vs. critical acceleration ratio (K_c/K_m) and upper bound lines

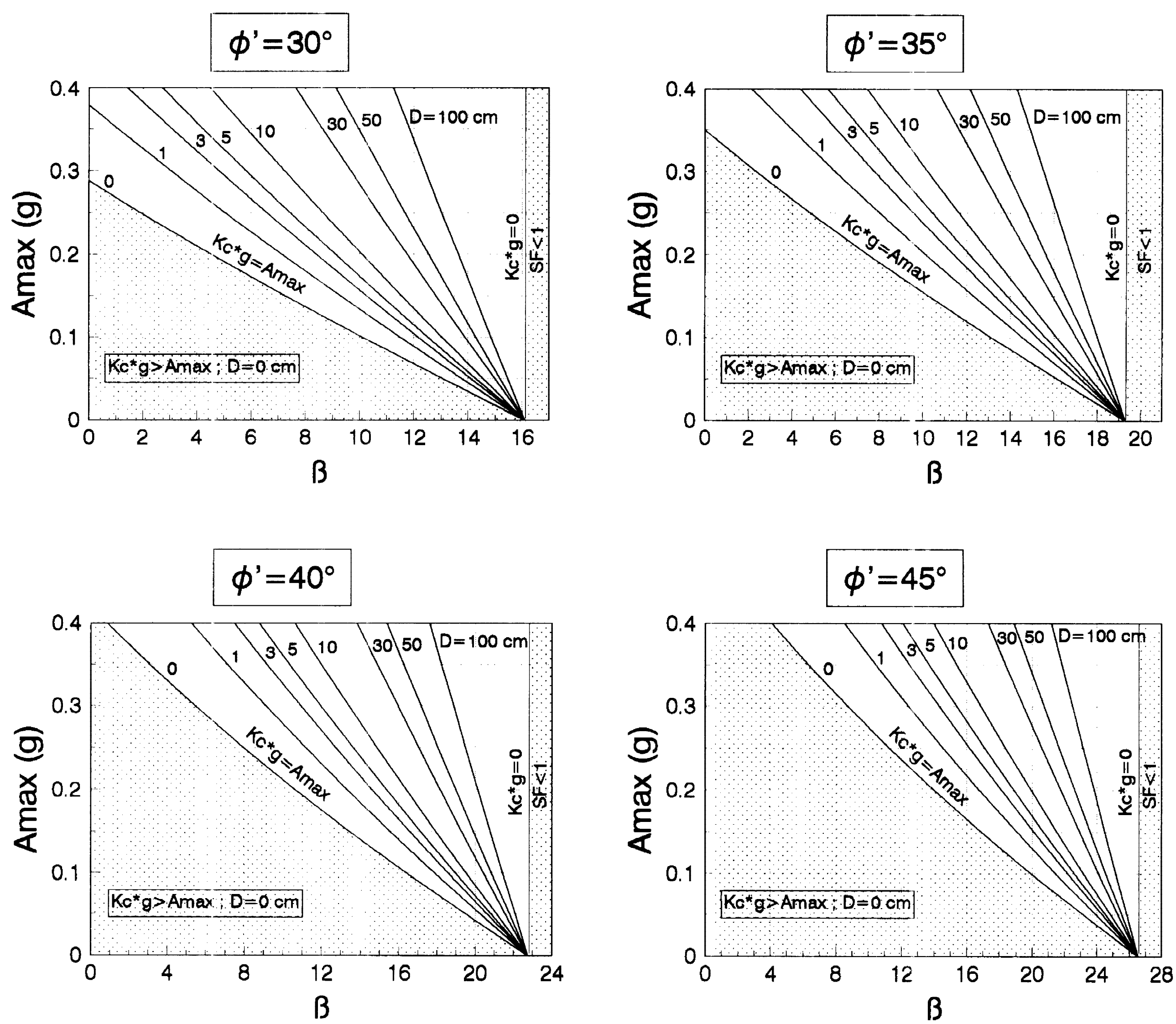

Fig. 5. Indefinite slope and saturated cohesionless soil: Design Charts for different friction angle values

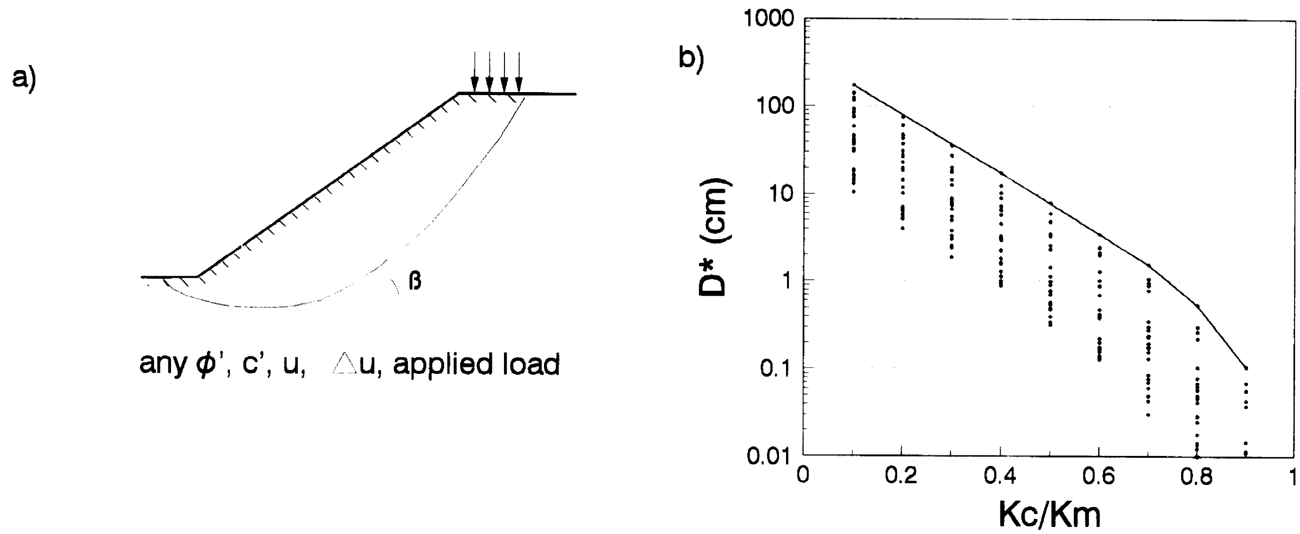

Fig. 6. a) Scheme of soil-slope configuration (case C)
b) Displacement D^* vs. critical acceleration ratio (K_c/K_m) and upper bound lines

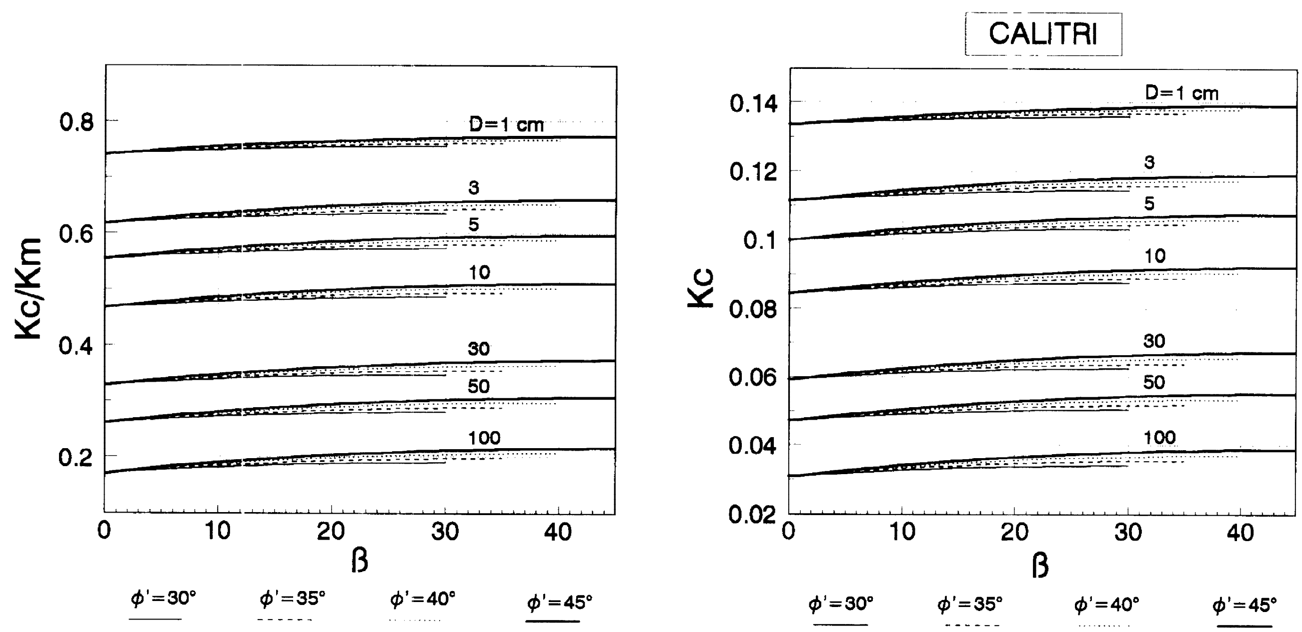

Fig. 7. a) Design Chart (case C): critical acceleration ratio (K_c/K_m) versus β for given D and ϕ' values
b) Design Chart for Calitri site (A_{max}=0.18): K_c vs. β for given D and ϕ' values

the other two parameters is defined. In this case a reduced displacement D^* is defined as

$$D^* = \frac{D}{\left[\frac{\cos(\phi' - \beta)}{\cos\phi'}\right]} \tag{5}$$

Displacements D^* have been computed by the integration of equation (4) (assuming $[\cos(\phi'-\beta)/\cos(\phi')]=1$) for assigned values of K_c (hence of K_c/K_m). Displacement results vs. the critical acceleration ratio and the relevant upper bound correlation function are plotted in Fig.6b.

For assigned values of friction angle ϕ' and direction β, the correlation function previously defined allows

the direct correlation of the maximum permanent displacement D with K_c/K_m. In the Design Chart illustrated in Fig.7a, iso-displacement curves are plotted for ϕ' values equal to 30°, 35°, 40° and 45°. It clearly appears that the effect of K_c/K_m on displacement is predominant; nevertheless it must be observed that the critical acceleration coefficient K_c itself is function of ϕ' and β values. This Design Chart can be utilized in different ways, both as design and verification tool. For instance, in design problems where ϕ' and β are fixed, the chart indicates the K_c/K_m value relevant to a given allowable displacement; if a lower value of K_c is obtained by the back analysis procedure, the initial configuration has to be corrected (e.g. modifying the slope profile, the pore pressure regime or the distribution of the applied loads).
For given A_{max} values specific charts can be drawn, which directly provide the value of the critical acceleration coefficient K_c; e.g. the Design Chart for Calitri site (A_{max}=0.18) is illustrated in Fig.7b.

CONCLUSIONS

The effects of different mechanical soil properties, pore pressure distributions and geometrical configurations on displacement based seismic design have been studied. Irpinia seismic data have been adopted as reference input motion. Three typical soil-slope configurations have been examined. For each of them the correlation function between maximum permanent displacement and critical acceleration ratio has been defined, in order to account for the effect of the waveform characteristics of the whole set of the accelerometric time histories. The results have then been synthetised in Design Charts which correlate the maximum acceleration expected at the site with soil-slope characteristics, for given value of the maximum permanent displacement.

For the case of indefinite slope in dry cohesionless soil, the response is function of the difference between the soil friction angle ϕ' and the slope inclination β; hence a unique Design Chart correlates displacements directly to slope (ϕ'-β) value. For saturated soil, the displacements depend on the single values of ϕ' and β; several Design Charts have been drawn, for different values of the friction angle. The effects of soil saturation are a drastic reduction of the critical acceleration coefficient K_c, hence a significant increase in the suffered displacements and more severe design indications.

Proper Design Charts can be utilized also for the case of complex soil-slope configuration, provided that the direction of the relative motion β can be preliminarly defined. In this case the charts correlate the displacements to the soil friction angle ϕ', to the motion direction β and to the critical acceleration coefficient K_c, which has to be compared to the value obtained by a back-analysis procedure.

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