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Selection of Method for Seismic Slope Stability Analysis

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SYNOPSIS: The seismic stability of natural slopes in clayey materials is a subject about which much uncertainty still exists. Therefore, selection of the method for the seismic slope stability analysis is an important part of solving the problem. In this paper the basic elements of the pseudo-static method, the sliding block method and the Ishihara's method are discussed. A case history of seismic stability analysis of an Adriatic coast flysch slope has been employed to evaluate the applicability and reliability of these methods. The slope is treated as an infinite slope. Although no definitive conclusions can be drawn from a single case history study, results may be used in future evaluations of seismic stability of similar slopes in cohesive materials.

INTRODUCTION

The sliding of natural slopes usually occurs during, or follows strong earthquakes. In most cases such sliding is governed by a combination of geological conditions and earthquake loading. Although various modes of seismically induced failures have been identified and classified (e.g., Keefer, 1984), it is still very difficult to analytically forecast the failures. The most important reasons for that are the difficulties associated with the determination of reliable material parameters on the contact of different layers, usually expensive and inadequate characterization of the material behavior under irregular cyclic loading and the uncertainty associated with the evaluation of seismic loads that are never explicitly known. In other words, the accuracy of the methods of numerical analysis greatly exceeds the accuracy with which the required numerous geotechnical and seismical parameters can be estimated.

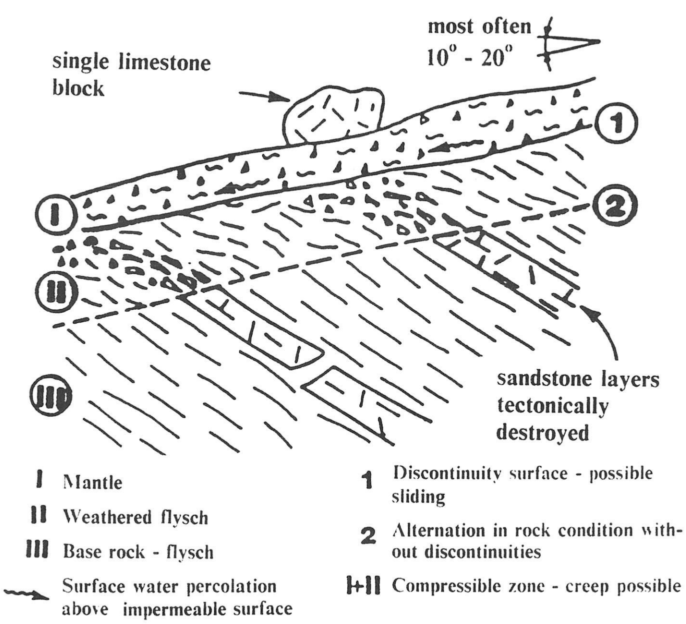

Fig. 1 Engineering geology elements of a flysch slope (After Jurak et al., 1987)

To examine various approaches to the seismic stability analysis of natural slopes in clayey materials, given the difficulties mentioned above, a seismically induced failure of a slope is analyzed in this paper. The failure was reported after the 1979 Montenegro earthquake ($M_L = 7.1$) in a small village, Velji Kaliman, Yugoslavia. Movement of a mantle on a flysch base was along well defined sliding surface. The sliding mass was of constant height and approximately 500m long. Engineering geology elements of the slope, which represents a rather typical flysch slope of the Adriatic coast, are shown in Figure 1 (Jurak et Al. 1987, after Ivanovic, 1979). The infinite slope model employed has been modified to meet specific requirements of modeling the flysch slope. The seismic stability analysis was provided using three of the most popular analytical methods.

METHODS FOR SEISMIC SLOPE STABILITY ANALYSES

Today, the evaluation of the seismic stability of natural slopes in clayey materials is most often carried out using various modifications of the following three methods: the pseudo-static method, the sliding block method (Newmark, 1965) and the Ishihara's method (Ishihara, 1985).

Analysis by Pseudo-static Method

The pseudo-static method for seismic slope stability analysis is based on assumptions of the limit equilibrium and is still the most popular method among practicing engineers. In addition to the vertical force G, (Figure 2a), which can be expressed as a product of the total mass m and the acceleration of gravity g, horizontal force $H = k_s G$ proportional to G is introduced to simulate earthquake loading. The proportionality factor, k_s is called the *seismic coefficient*. If the infinite slope model is used, additional assumptions have to be introduced as follow:

- the sliding surface is a straight plane parallel to the surface
- interslice forces are equal in every vertical cross section and parallel to the ground surface
- the direction of steady state seepage is parallel to the ground surface
- sliding mass is affected by pseudo-static inertia force proportional to its total weight and parallel to base acceleration
- the base acceleration is horizontal

- the magnitude of acceleration is constant in the soil mass above the sliding surface, i.e. free field acceleration is applied at the bottom of the slice
- there is no pore pressure increase in the soil mass during shaking.

The influences of the vertical acceleration component and the pore pressure increase during shaking (flysch is partially saturated cohesive material) are neglected because it is believed they are small in this particular case.

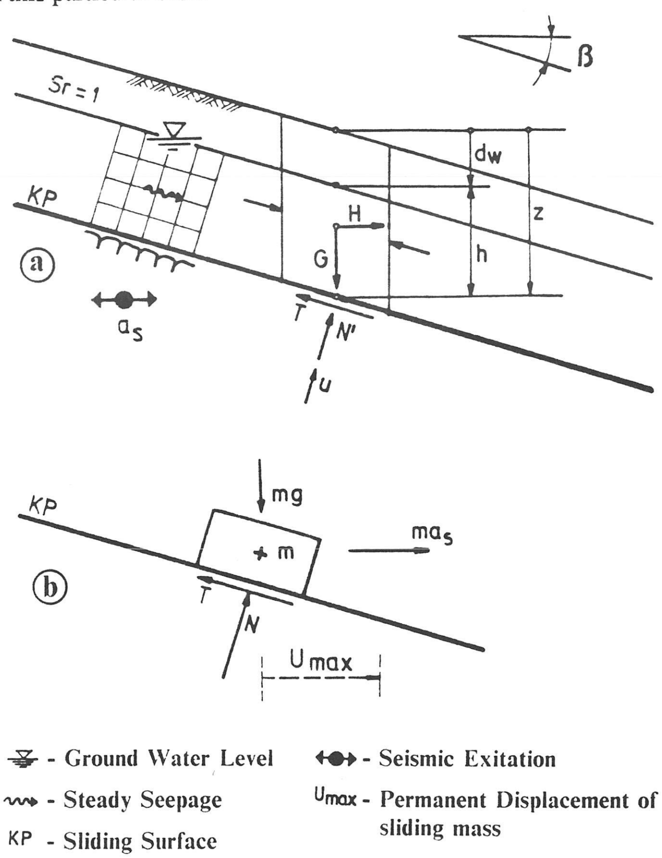

Fig. 2 Model of an infinite slope

Based on the above assumptions, the principles of limit equilibrium and the notation introduced in Figure 2, the following expression for the factor of safety, F_s, has been derived (Matasovic, 1989):

$$F_s = \frac{c/(\gamma\, z \cos^2 \beta) + \tan \Phi [1 - \gamma_w (z - d_w)/(\gamma\, z)] - k_s \tan \beta \tan \Phi}{k_s + \tan \beta} \qquad (1)$$

where γ, γ_w, c and Φ are the unit weight of slope material, the unit weight of water, cohesion and the angle of internal friction respectively.

Equation (1) defines the factor of safety for a general case of infinite slope stability. A similar expression, but for stability of cohesionless materials with pore pressure increase due to seismic loading, has been used by Hadj-Hamou and Kavazanjian (1985).

It should be noted that the value of factor of safety calculated by Equation (1) diminishes with depth in cohesive ($c \neq 0$, $\varphi \neq 0$) materials. Also, since the equation has been set for a case of limit equilibrium when $F_s = 1$, it is assumed that slope will generally resist seismic loading and will be stable if $F_s > 1.0$.

Analysis by sliding block method

The sliding block method (Newmark, 1965) has been universally applied in dam engineering. Basic elements of slope stability analysis by this method are shown on an idealized model of an infinite slope in Figure 2b. According to D' Alembert's principle, under seismic excitation of the base a_s, the reaction of the sliding weight G would be the pseudo-static inertial force $m\, a_s = k\, G$. The limiting value of that inertial force, i.e. the limiting value of the acceleration because the mass is constant, which leads mass to the state of the limit equilibrium, depends on the shear resistance of material on a sliding surface. This acceleration is called critical acceleration, a_{sc} and can be expressed as $a_{sc} = k_c\, g$, where g is the acceleration of gravity and k_c is the factor of proportionality called *coefficient of critical acceleration*. According to the premises of this method, if the critical acceleration is exceeded, a sliding of the mass will occur. After each increment of shaking with acceleration greater than a_{sc} and associated down slope sliding, the mass will stop in a new position with respect to its original location. At the end of shaking such increments of dislocation will amount to a final and maximum permanent displacement of the sliding mass, u_{max}.

To estimate u_{max}, it is necessary, as a first step, to determine a_{sc} expressed by the product $k_c\, g$. The coefficient k_c can be determined iteratively by varying the amount of horizontal force until it reaches the value that gives the $F_s = 1$. However, for the model of infinite slope the coefficient of critical acceleration can be expressed explicitly by inserting $F_s = 1$ in Equation (1) and rearranging the variables:

$$k_c = \frac{c / (\gamma\, z \cos^2 \beta) + \tan \Phi\, [1 - \gamma_w (z - d_w)/(\gamma\, z)] - \tan \beta}{1 + \tan \beta \tan \Phi} \qquad (2)$$

For a case without steady state seepage in the slope (if we insert $d_w = z$), Equation (2) becomes the expression for k_c used by Chang et Al. (1984).

After the critical acceleration has been determined, permanent displacements can be estimated by using various close form solutions available (e.g., Ambraseys and Menu, 1988), or by treating the appropriate accelerogram using the Makdisi and Seed (1978) procedure based on Newmark's (1965) approach.

The main practical problem related to the application of sliding block method in analysis of natural slopes is how to define the allowable permanent displacement. The limits on calculated values could be related to functionality of structures on the slope or to the stability of the slope itself after the earthquake. For example, if an earthquake has caused cracking of the slope, water percolation in earthquake opened cracks can significantly change the static stability. One of a very few tentative criteria set for natural slopes is the one established by the State of Alaska's Geotechnical Evaluation Criteria Committee, given in Table 1 (based on 1964 Great Alaskan Earthquake, quoted in Idriss, 1985).

TABLE 1. Orientational stability criteria for the sliding block seismic stability analysis of natural slopes

Failure Category (State of Alaska Criteria)	Amount of Corresponding Perm. Lat. Displacement
I Catastrophic Ground Failure	300 cm
II Major Ground Adjustment	90 cm
III Moderate Ground Adjustment	30 cm
IV Minor Ground Adjustment	15 cm
V Little or no Ground Adjustment	< 3 cm

Analysis by Ishihara's method

An interesting approach to the seismic analysis of natural slope stability has been proposed by Ishihara (1985). The main difference from the pseudo-static method is the definition of the seismic loads and the estimate of the dynamic shear strength of soils. Instead of k_s, the ratio a_{max}/g is used while the dynamic strength of soils is determined by loading the specimen in a triaxial apparatus with an irregular load history that is proportional to the selected accelerogram. Thus, the factor of safety of an infinite slope can be also determined in terms of Isihara's method, i.e. by using the Equation (1), stability criteria of pseudo-static method, and seismic loads and shear strength parameters determined in above mentioned way.

Ishihara (1985) showed that this method provides good results in the back calculated analyses. However, since shear strength parameters depend on a priori unknown loads, a good engineering judgment is needed for selection of the seismic load and corresponding prediction of slope sliding. Also, its practical application is related to non standard cyclic triaxial tests and it is therefore quite expensive. To avoid these shortcomings, Ishihara (1985) suggested tentative criteria for dynamic shear strength estimation based on static test data, which are discussed later in detail.

SELECTION OF SEISMIC LOADS PARAMETERS

Earthquakes are very complex natural phenomena with forces that are practically impossible to accurately simulate or quantify. In addition to forces generated by shear and compressive waves, there are two types of surface waves, both acting simultaneously, which add to the complexity of the applied dynamic loads. In engineering calculations, the problem is usually simplified by using time histories of the ground surface accelerations. However, the ground surface accelerograms are in general, still too complicated to be used in routine seismic stability analyses of natural slopes. Also, it is impossible to accurately predict their shape, length and frequency. Therefore, in engineering practice the characterization of the seismic load is further simplified by using a simple value of the ground surface acceleration. It is evident that it would be too conservative to select for this purpose the peak value of the strong motion record, a_{max}, because it lasts for a very short time and appears only once in the record. So, instead of a_{max}, it's fraction $k_s\ a_{max}/g$ is used, where k_s is called *the seismic coefficient*.

Different magnitudes of k_s have been proposed by various authors, mostly based on back analysis of actual cases and compilation of empirical data. For example Marcuson (1981) stated that the appropriate value of the k_s probably lies between 1/2 and 1/3 a_{max}/g when seismic stability of earthfill dams and embankments is analyzed and amplification of the earth structure is included in a_{max} value. Matsuo et Al. (1984) recommended 0.65 a_{max}/g, as quoted and used by Taniguchi and Sasaki (1985) in back analysis of a landslide. These two recommendations are combined in Figure 3.

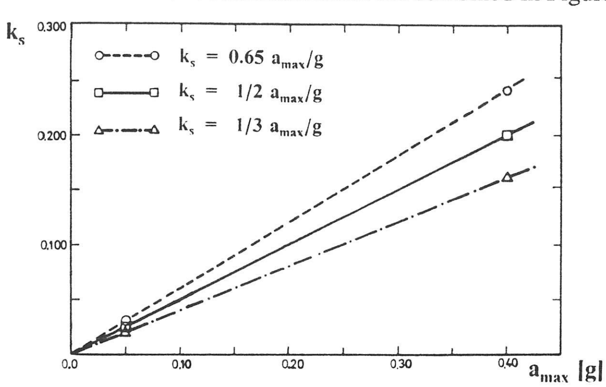

Fig. 3 Seismic coefficient related to the peak gnd. acceleration

It can be seen that, when describing seismic loadings by seismic coefficient, an additional assumption is introduced into seismic stability analysis. Using the sliding block method, the stability criteria are rough and not completely clear. On the other hand Ishihara's method avoids these two problems, but additional assumptions on the shear strength of the material during seismic loading are introduced.

SELECTION OF SHEAR STRENGTH PARAMETERS

When studying the seismic stability of natural slopes, particular care should be devoted to the evaluation of the shear strength parameters of the material. Because the shear strength of a material depends on the rate of loading, it is correct to choose material parameters that correspond to the rate of seismic loading and initial state of stresses immediately before the earthquake shaking. The rate of pore pressure buildup and simultaneous dissipation due to existing drainage conditions also should be considered. This can be simulated the best by the Ishihara's method, which however involves a quite expensive laboratory testing.

In practice, when it is not possible to perform complex experimental investigations, shear strength parameters are usually obtained in a fast direct shear tests, on fully saturated cohesive specimens consolidated to initial state of stresses acting before seismic excitation. However, to check whether significant drop of strength during shaking with respect to static direct shear strength can be expected, recommendations by Silver (1987) based on simple classification tests and summarized in Figure 4 can be used.

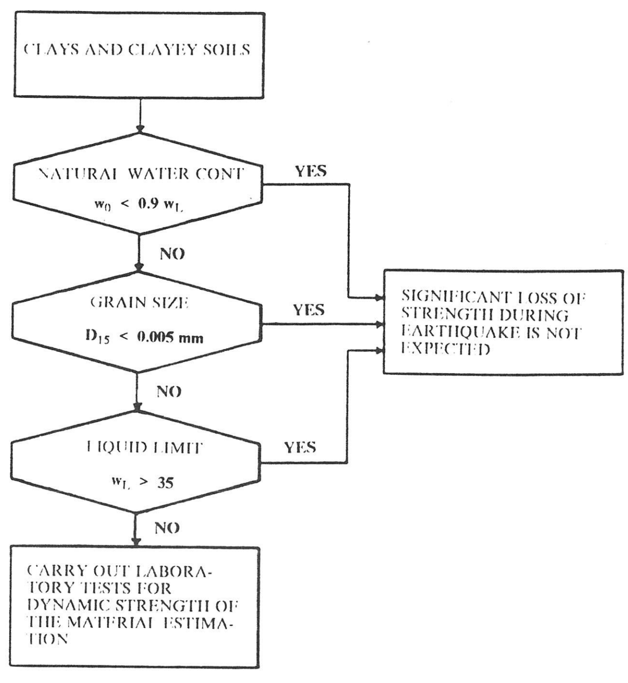

Fig. 4 Flow chart for preliminary dynamic stability of cohesive soil estimation (After Silver, 1987)

Another aspect to look at is whether "in situ" shear strength of cohesive soils during earthquake shaking is always smaller than the strength in static conditions. Ishihara (1985) noticed on unsaturated specimens of volcanic sandy clays that the cohesion value under drained dynamic loading is at least 60% greater than the one under static loading. He also noticed that the strength increase is higher in materials having higher plasticity index (I_p), while the angle of internal friction remains approximately the same. Based on that, Ishihara suggested seismic analyses carried out with static cohesion values increased by 50% while using seismic coefficient defined by ratio a_{max}/g. This is called in this text the simplified Ishihara's method.

The expected behavior of the material during seismic excitation also can be a key factor for choosing the appropriate slope stability analysis method. Ishihara (1985) has noticed that there is no use in calculating permanent displacement in very brittle materials, where among the others, pseudo-static methods provide acceptable results. Wroth and Houlsby (1985) stated that the clay samples with low values of OCR deform generally in a ductile manner. The commonly used criterion OCR < 5 has been selected on flow chart in Figure 5 as a tentative value for distinguishing brittle and ductile clayey materials in which is reasonable to calculate permanent displacements. The post cyclic behavior of the material on Figure 5 has been characterized by another tentative criterion, based on Vaughan and Walbancke observation (quoted in Wroth and Houlsby, 1985) that significant drop in strength only occurs in clays with a plasticity index greater than about 26% and where very large shear deformations have occurred.

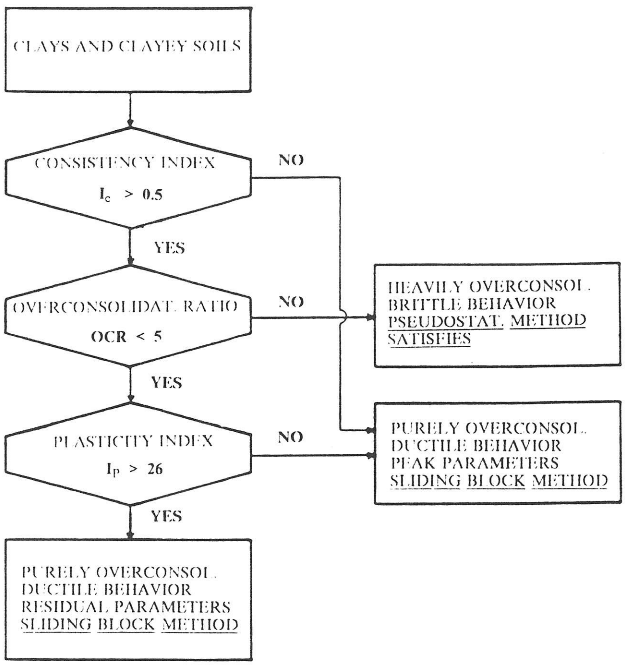

Fig. 5 Flow chart for selecting adequate seismic stability analysis method

THE VELJI KALIMAN CASE HISTORY

To examine the applicability of the seismic stability analysis methods described above, a stratigraphycally simple landslide has been selected (Figure 1). The slide occurred after the Montenegro earthquake of April 15, 1979 (M_L = 7.1) in a small village Velji Kaliman, Yugoslavia, about 11 km north of the town of Ulcinj (see Figure 6). Although the cracks occurred during the earthquake, the sliding started two days later after heavy rains. The sliding mass was approximately 500m long, 200m wide, 5m high and inclined to the horizontal at 15° (Ivanovic, 1979). Since flysch slopes are sensitive to water percolation through contact of mantle and weathered flysch, it was concluded that sliding was induced along the contact by water inflow in the earthquake opened cracks.

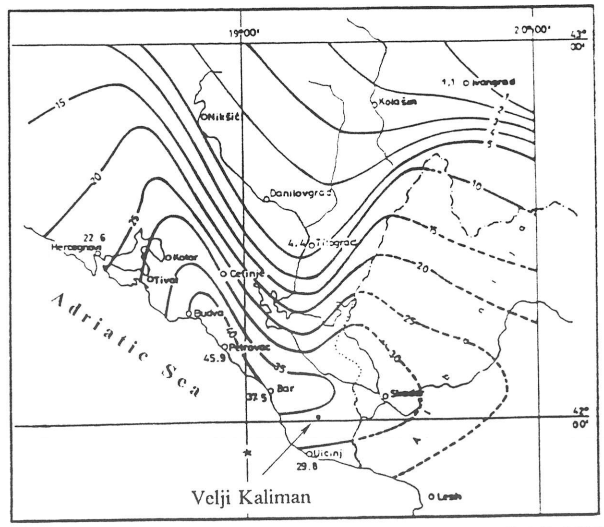

Fig. 6 Isolines of amax [g] distribution during April 15, 1979 Montenegro earthquake (After Petrovski et al., 1979)

The maximum acceleration value at the site of 0.34g is estimated by linear interpolating between the maximum acceleration isolines presented by Petrovski et Al. (1979), as shown in Figure 6. Given this estimate, the maximum permanent displacement has been calculated by the sliding block method using N-S component of the accelerogram *ULCINJ-2* (IZIIS, 1984). For comparison, the same accelerogram was scaled to different acceleration levels and the permanent displacement curve, plotted in Figure 7 by the solid line, was obtained. It is evident that the calculated curve is in good agreement with the dashed lines curves reproduced from Makdisi and Seed (1978) that were obtained by the same methodology. These two curves also represent the band of possible permanent displacements induced by earthquakes of M_L 7.5, which is close to the Montenegro earthquake magnitude.

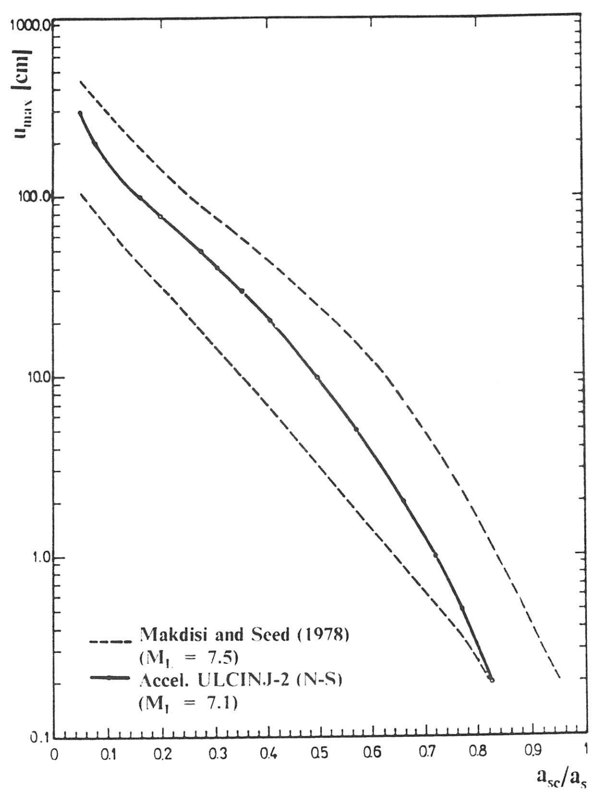

Fig. 7 Permanent displacement estimation chart

Engineering geology elements of the sliding are shown on Figure 1. More details, as well as physical and mechanical properties of the Adriatic coast flysch, can be found in Ivanovic (1979) and Jurak et Al. (1987). These studies show that the following average values are typical for the weathered flysch: $w_L > 35$; $D_{15} < 0.005$ mm; $w_0 < 0.9w_L$; $I_c > 0.5$; $OCR < 5$; $I_p > 26$; $\gamma = 22$ kN/m^3; $82 < S_r < 85\%$, where index properties have been defined on Figures 4 & 5, D_{15} is the grain diameter (in mm) corresponding to 15% passing by weight and S_r is the degree of saturation. The average values of the shear strength parameters were also adopted from above mentioned studies and are summarized in Table 2.

The analyses were performed using expressions (1) and (2). The steady state seepage parallel to the slope was assumed. Based on $a_{max} = 0.34$g, the value $k_s = 0.18$ was chosen as a mean value from Figure 3. Since the weathered flysch is pretty similar by its composition and saturation to the properties of materials Ishihara (1985) tested, and since the empirical criteria from Figure 4 do not predict any loss of strength during shaking, it was possible to hypothesize that dynamic cohesion of weathered flysch could be higher than the static one. Thus the calculations by simplified Ishihara's method were carried out by using the same Φ as in the static case, but the cohesion value was increased by 50%. Basic elements and results of the analysis are summarized in Table 2.

TABLE 2. Basic elements of stability analyses

	Analysis Type			
Parameter	Static	Pseudo--static	Sliding block	Ishihara's simplified
c [kPa]	25	25	25	38
Φ [deg]	23	23	23	23
a_s [g]	-	0.34	0.34	0.34
k_s [-]	-	0.18	0.34	0.34
k_c [-]	-	-	0.186	-
F_s [-]	1.77	1.01	-	0.93
u_{max} [cm]	0	-	5	-

For the pseudo-static and simplified Ishihara's method analysis values of F_s are also calculated for different levels of assumed a_{max} and are shown in Figure 8.

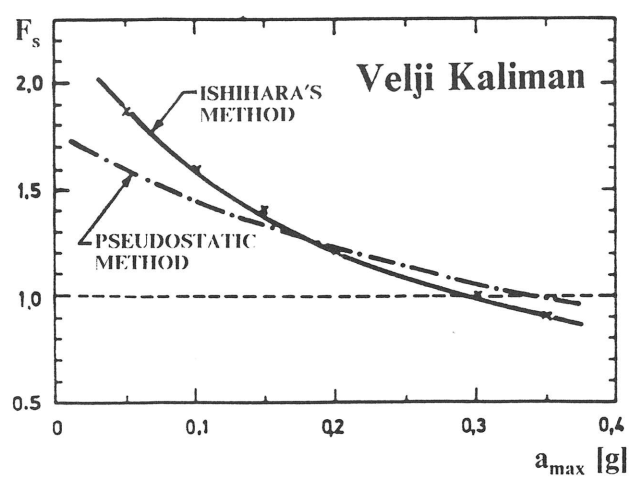

Fig. 8 Summary of analysis results

Figure 8 shows that Ishihara's method is more sensitive to the magnitude of the seismic loads than conventional pseudo-static method. Both methods reach the zone of instability close to 0.34g. On the other hand the sliding block analysis gave permanent displacement of about 5cm (minor ground adjustment, see Table 1). Application of the tentative criteria from Figure 5 on given material properties leads to the conclusion that this is also acceptable result.

CONCLUSIONS

The seismic stability of natural slopes is a subject about which much uncertainty still exist. The main problems associated with predicting slope behavior during and after earthquake shaking are connected with selection of shear strength parameters of the material and estimation of adequate seismic loadings.

All three analyses provided here are in agreement. The pseudo-static method and the simplified Ishihara's method did not give complete failure, but they indicated instability ($F_s \approx 1$). The sliding block method calculated relatively small permanent displacement. All these point to cracks that actually developed during the shaking. Subsequent slide is another matter.

The flow chart shown in Figure 4 is useful as a starting point for the estimation of eventual material strength loss during shaking, assessing whether simplified Ishihara's method can give reasonable results and, if there is a need for carrying out expensive laboratory tests. It is shown that, if criteria from Figure 4 are applied to the average value of Adriatic coast flysch parameters, they do not predict loss of strength during shaking. Whether there is some strength increase is still not completely clear, although weathered flysch is similar to the materials in which the increase was observed. The assumption on 50% cohesion value increase in weathered flysch should be examined by irregular cyclic tests. After that, the applicability of Ishihara's methods in flysch materials can be finally evaluated.

The flow chart from Figure 5 should help with dilemmas about whether to carry out the stability analysis by the pseudo-static or by the sliding block method. If these criteria are applied on the average values of the Adriatic coast weathered flysch it turns out that the application of the sliding block method can give acceptable results.

Finally, no definitive conclusion can be drawn from a single case history study. All hypotheses set and conclusions derived here should be further examined by analyzing other case histories to derive general conclusions on applicability of the pseudo-static method, the sliding block method and Ishihara's method for seismic analyses of natural slopes in cohesive materials.

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REFERENCES

Ambraseys, N.N. and Menu, J.M. (1988), "Earthquake-Induced Ground Displacements," Earthquake Engineering and Structural Dynamics, Vol. 16, pp. 985-1006.

Chang, C-J., Chen, W. and Yao, J.T.P. (1984), "Seismic Displacements in Slopes by Limit Analysis," Journal of Geotechnical Engineering, ASCE, Vol. 110, No. 7, pp. 860-874.

Hadj-Hamou, T. and Kavazanjian, E. (1985), "Seismic Stability of Gentle Infinite Slopes," Journal of Geotechnical Engineering, ASCE, Vol. 111, No. 6, pp. 681-697.

Idriss, I.M. (1985), "Evaluating of Seismic Risk in Engineering Practice," Proc. 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, Vol. 1, pp. 255-320.

Ishihara, K. (1985), "Stability of Natural Deposits During Earthquakes," Proc. 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, Vol. 1, pp. 321-376.

Ivanovic, S. (1979), "Slidings, Avalanches and Slope Stability Problems in Southern-East Part of Outer Dinarics (Coastal Region from Bojana to Split)," Ph.D. Thesis, Faculty of Mining and Geology, University of Belgrade, Belgrade, Yugoslavia. (In Serbo-Croatian).

IZIIS, (1984), "Corrected Accelerograms and Integrated Ground Velocity and Displacement Curves," Bulletin No. 1, Institute of Earthquake Engineering and Engineering Seismology, University "Kiril and Metodij," Skopje, Yugoslavia.

Jurak, V., Matasovic, N., Cvijanovic, D., Jasarevic, I., Garasic, M. and Slovenec, D. (1987), "Defining of the Natural Conditions of the Zupa Dubrovacka Area for the Needs of Geotechnical-Seismic Microzonation," Proc. 9th Yugoslav Symposium on Hidrogeology and Engineering Geology, Pristina, Yugoslavia, Vol. 2., pp. 41-60. (In Croatian).

Keefer, D.K. (1984), "Landslides Caused by Earthquakes," Geological Society of America Bulletin, Vol. 95, pp. 406-421.

Makdisi, F. and Seed, H.B. (1978), "Simplified Procedure for Estimating Dam and Embankment Earthquake-Induced Deformations," Journal of the Geotechnical Engineering Division, ASCE, Vol. 104, No. GT7, pp. 849-867.

Marcuson, W.F. (1981), "Earth Dams and Stability of Slopes Under Dynamic Loads," Moderators Report, Proc. International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, University of Missouri-Rolla, Rolla, Missouri, Vol. 3, pp. 1175.

Matasovic, N. (1989), "Seismic Stability of Flysch Slopes," Gradjevinar - Journal of the Croatian Society of Civil Engineers, Vol. 41, No. 7, pp. 341-348 (In Croatian)

Newmark, N.M. (1965), "Effects of Earthquakes on Dams and Embankments," Géotechnique, Vol. 15, No. 2, pp. 139-160, London.

Petrovski, J., Petrovski, D., Naumovski, N. and Zelenovic, V. (1979), "Strong Motion Characteristics and Acceleration Distribution During Montenegro April 15, 1979 Earthquake," Proc. International Research Conference on Intra-Continental Earthquakes, Ohrid, Yugoslavia, pp. 137-155.

Silver, M. (1987), "Slope Stability," IAEA Workshop on Special Requirements for Design and Construction of Civil Structures, Zagreb, Yugoslavia, 115. pp.

Taniguchi E. and Sasaki, Y. (1985), "Back Analysis of a Landslide Due to the Naganoken Seibu Earthquake of September 14, 1984," Proc. 11th International Conference on Soil Mechanics and Foundation Engineering, Discussion 7b - Strength Evaluation for Stability Analysis, San Francisco, pp. 1-6.

Wroth, C.P. and Houlsby, G.T. (1985), "Soil Mechanics-Property Characterization and Analysis Procedures," Proc. 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, Vol. 1, pp. 1-55.