Slope stability analysis according to EC-8 and Italian seismic regulations

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Abstract

The aim of the paper is to compare the results of slope stability analyses performed according to Eurocode 8 (EC-8) with those obtained by the pseudo-static approach of the pre-existing Italian seismic code (D.M. 16.1.1996). In applying the European code to the simple case of a dry, infinite and incoherent slope the acceleration values defined in the recent Italian seismic zonation (OPCM 3274/2003) have been utilised for determining both the pseudostatic and pseudo-dynamic actions. Although it may not be possible to make an immediate comparison of the different design methods in that they make use of non "homogeneous" seismic actions, it may be observed that the Eurocode 8 pseudo-static method, combined to the Italian OPCM 3274 ground accelerations, leads to a much more conservative design than that obtained by the pre-existing Italian seismic regulation. On the other hand, more reliable Newmark displacement analyses, performed according to EC-8, do not confirm the results of the EC-8 pseudostatic method. This evidence suggests that more work has to be done in defining the parameters and coefficients to be entered in the EC-8 pseudo-static procedure.

INTRODUCTION

Traditionally the seismic stability of both natural and artificial slopes has been evaluated by the classical pseudostatic approach where the seismic actions are traduced in equivalent static forces by means of the so-called seismic coefficients. They are related to the seismic intensity observed at the site and specified in national codes.

In recent years, more advanced approaches have been tested and validated such as the pseudo-dynamic approaches (Newmark method or its derivatives) or dynamic approaches solved numerically by different techniques (FEM, FDM, etc.). Both pseudodynamic and dynamic approaches model the earthquake in a more realistic way generally by utilising a time-acceleration function.

More advanced approaches have been contemplated in recent European codes (see Part 1 (EN 1998-1) and Part 5 (EN 1998-5) of Eurocode 8, henceforth indicated as EC-8) and national codes such as the Italian regulation OPCM 3274 of March 2003. In these documents, however, the classical pseudo-static approach is still contemplated but the seismic coefficients have been correlated to the maximum ground acceleration expected at the site.

In this paper the Italian seismic regulation OPCM 3274 will often be recalled, which acknowledges Eurocode 8 criteria. Further, it proposes initial values of parameters such as the reference peak ground acceleration agR, the soil factor S, etc., which are required to perform pseudostatic, pseudodynamic or dynamic analyses in the spirit of the Eurocodes. In this sense it could be intended as a National Annex.

The objective of the paper is to compare the results of slope stability analyses performed in the traditional way as suggested in the old Italian seismic regulation (D.M. 1996) and those obtained by applying the more recent EC-8 and OPCM 3274 normative.

In the paper the above objective is attained in two stages:

1) comparing the results of the pseudostatic analyses performed by following the old Italian seismic code (D.M. 1996) and the new criteria

of EC-8 (combined to OPCM 3274 ground accelerations);

2) comparing the results discussed at the previous item with those obtained applying the Newmark method (according to EC-8 criteria and OPCM 3274 acceleration values).

METHODS OF ANALYSIS

The pseudostatic approach is the most consolidated method adopted to analyse slope stability under seismic actions. This popularity, especially in the professional field, may be due to the fact that the pseudostatic approach is very simple and further it was the only one contemplated in old seismic codes.

Referring to literature for the basic concepts of the method, only some features will be recalled. The method assumes that the earthquake actions are represented by equivalent static actions F_h and F_v acting both horizontally and vertically, whose magnitudes are proportional to the weight W of the unstable mass by means of the so-called seismic coefficients K_h and K_v:

$$F_h = K_h \cdot W \tag{1}$$

$$F_v = K_v \cdot W \tag{2}$$

The method consists in comparing the resisting forces acting along the failure surface to the driving ones. The failure surface is not known *a priori* and should be found tentatively. The ratio between the resisting and the driving forces represents the pseudostatic safety factor, PSF, which allows to assess the slope stability. In the particular case of a dry, infinite and incoherent slope the PSF has the following expression:

$$PSF = \frac{[(1-K_v)W\cos\beta - K_h W \sin\beta]tg\varphi'}{[(1-K_v)W\sin\beta + K_h W\cos\beta]} \tag{3}$$

where φ' is the friction angle and β is the slope inclination with respect to the horizontal direction.

In spite of its simplicity, the crucial aspect of the pseudostatic approach is the equivalence criterion between the pseudostatic forces, constant in time and space, and the earthquake actions, variable in time and space. As a matter of fact the analysis results are strongly dependent on values assigned to the seismic coefficients K_h and K_v.

The seismic stability of a slope can be assessed also on the basis of its performance during the earthquake; the performance can be evaluated by means of the pseudo-dynamic or dynamic approaches. Among these, the simple Newmark model (1965) allows the evaluation of the final displacement suffered by the slope at the end of the earthquake. The earthquake action is represented in a more realistic way, by means of a time-acceleration function. To assess the safety condition of a slope under seismic actions, the computed displacement should be compared to an admissible limit value which depends on the slope boundary conditions (performance based design) and has therefore to be defined for the particular case in hand. The magnitude of the seismic-induced displacement is strongly dependent on the accelerogram features: peak value, length and frequency content. These features vary with the earthquake source mechanism, the seismic wave pattern and with the nature of soils at the specific site which may induce amplification phenomena. Hence, for a correct prediction of the final displacement the Newmark method requires a suitable choice of the input motion set. This aspect is crucial especially when applying the method in the professional field.

As well known, the Newmark model analyses the sliding of a rigid block on a plane surface, assuming a rigid-plastic behaviour at the interface between them (Fig 1). From simple limit equilibrium considerations, the threshold acceleration value a_c can be evaluated, above which the surface moves faster than the block, which instead still saves the threshold acceleration.

The relative displacement between the block and the surface can be computed by integrating relative accelerations twice, until the velocity between them returns to zero again.

The threshold acceleration a_c is given by:

$$a_c = k_c\, g \tag{4}$$

where k_c is the critical acceleration coefficient which can be determined by a pseudostatic analysis imposing a unit safety factor (PSF=1).

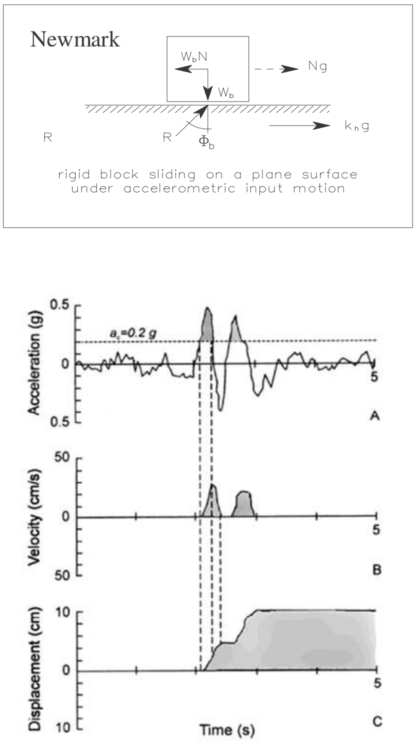

Fig 1: Newmark (1965) model for displacement analysis

The threshold acceleration a_c is therefore function of the geometrical and mechanical properties of the slope. For the simple case of a dry, infinite and incoherent slope the expression of the critical acceleration coefficient is very simple (Simonelli, 1993):

$$k_c = tg(\varphi' - \beta) \qquad (5)$$

where φ' and β have been already defined. From the above two equations it emerges that the threshold acceleration is only function of the difference between φ' and β and does not depend on their single values.

The differential equation regulating the relative displacement $U(t)$ between the block and the surface is given by:

$$\frac{d^2U(t)}{dt^2} = \frac{\cos(\varphi'-\beta)}{\cos\varphi'}\left[a(t) - k_c g\right] \qquad (6)$$

Equation (6) indicates that for the simple case here considered, the relative displacement between the block and the surface markedly depends on the difference between φ' and β whilst the influence of the term 1/cosφ' is less relevant (Simonelli & Fortunato, 1996).

If the vertical component of the accelerogram is also taken into account, the threshold acceleration varies with the direction of the input motion (Sarma 1975 and 1999). In the simple case of a dry, infinite and incoherent slope the formulation of the critical acceleration coefficient and of the displacement equation can be found in Simonelli & Di Stefano (2001). The latter work actually shows that with reference to three seismic events occurred in Italy, namely the Friuli 1976, the Irpinia 1980 and the Umbria-Marche 1997 earthquakes, the influence of the vertical component of the motion on the computed final displacement is practically negligible.

ITALIAN SEISMIC CODES FOR SLOPE STABILITY ANALYSES

In Italy the reference codes regulating the seismic slope stability are the D.M. 1996, still in force, and the OPCM 3274/2003, still under revision, that for the most part acknowledges the Eurocode criteria. This paper will often recall these rules, hence a brief description of what they suggest on slope stability analysis will be provided.

In the past, the Italian codes classified the seismic areas into three categories (I, II and III) characterized by different degrees of seismicity (S=12, 9 and 6). A large part of the territory has not been recognized as seismic area. This classification was essentially based on maps of macro-seismic Intensity, derived from the observation of the effects induced by past earthquakes on the physical environment, on buildings and on people. The D.M. 1996 with reference to the above classification of the national territory, defines the seismic coefficients C which are equal to 0.1, 0.07 and 0.04, respectively for the seismic category I, II and III. In the D.M. 1996 the role played by the "local" soil conditions has been taken into account through the so-called foundation coefficient ε, that increases seismic actions by 30% only in the case of alluvial deposits of thickness varying between 5 and 20 m, overlying stiff soils or rocks. This coefficient thus represents a sort of magic number based exclusively on the nature of the deposit and not on quantitative evaluations of the real mechanical characteristics of the soils.

For the stability analysis of slopes the D.M. 1996 exclusively suggests the use of the pseudostatic approach, considering only the horizontal force F_h, thus disregarding the effect of the earthquake in the vertical direction. The equivalent pseudostatic force F_h is linked to the seismic coefficient C by the following relation:

$$F_h = C\,W \tag{7}$$

that is in all similar to equation (1) if it is assumed $C=K_h$.

In assessing the seismicity of a given area, the OPCM 3274 adopts the reference peak ground acceleration a_{gR}, which is the maximum acceleration on a stiff outcropping formation (later defined as ground type A). On the basis of the expected a_{gR}, 4 seismic zones have been defined as shown in Table 1.

Table 1: Peak ground accelerations on ground type A for the 4 seismic Italian zones (OPCM 3274)

Zone	a_{gR}
1	0.35 *g*
2	0.25 *g*
3	0.15 *g*
4	0.05 *g*

Moreover the OPCM 3274 takes into account the amplification of the seismic motion due to local soil conditions by identifying 7 different types of subsoil (ground types from A to E plus the special category S1 and S2) such as those defined in the EC-8-part 1.

For the first 5 types of subsoil (from A to E) an amplification factor of the acceleration a_{gR} is given, named soil factor S.

According to OPCM 3274, the soil factor assumes the following values: 1.0 for subsoil type A; 1.25 for subsoils B, C and E; 1.35 for ground type D. The special subsoil classes S1 and S2 require *ad hoc* studies for characterizing the site amplification. The OPCM 3274 further takes into account topography effects by means of the factor S_T which amplifies the ground acceleration for slopes with inclination greater than 15° and a difference in height greater than 30 meters. Recommended values of S_T are 1.2 and 1.4.

With respect to slope stability analysis the OPCM 3274, as EC-8, suggests the use of the pseudostatic approach taking into account both the horizontal and vertical forces given by:

$$F_h = \pm 0.5\, S\, S_T\,(\,a_g/g)W \tag{8}$$

$$Fv = \pm 0.5\, F_h \tag{9}$$

For particular slope conditions the use of dynamic approaches is contemplated, in which the seismic action is represented by means of accelerograms and the soil is described by suitable constitutive law simulating soil response under cyclic loading conditions.

In conclusion, the OPCM 3274 acknowledges the EC-8 criteria and proposes initial values of the parameters that must be defined nationally, such as a_{gR}, S and S_T, in order to determine the ground acceleration. In this study the OPCM 3274 therefore plays the role of a National Annex.

PSEUDOSTATIC ANALYSIS

As stated above, in order to compare the results of pseudostatic analyses performed in the traditional Italian way (D.M. 1996) with those derived from the application of EC-8 (combined to OPCM 3274), the simple case of a dry, infinite and incoherent slope has been considered. In such a context the simplicity of the selected case has been a prerequisite to better appreciate the differences among the results of the two approaches, since a huge difference in the definition of seismic actions exists: on the basis of the seismic coefficient in the D.M. 1996; on the basis of the peak ground acceleration for the EC-8.

In the case of a dry, infinite and incoherent slope the static safety factor SF is given by:

$$SF = \frac{tg\varphi'}{tg\beta} \tag{10}$$

If seismic actions are considered the pseudostatic safety factor PSF computed according to the old D.M. 1996 is given by:

$$PSF = \frac{tg\varphi'}{tg(\beta + arctgC)} \tag{11}$$

derived from equation (3) by considering $Kh=C$ and $Kv=0$.

The pseudostatic safety factor, considering the EC-8 or the OPCM 3274 normative, is given by the following equation:

$$PSF = SF\frac{(1-K_v) - Kh\ tg\beta}{(1-K_v) + \frac{Kh}{tg\beta}} \tag{12}$$

where:

$$Kh = S \cdot S_T \cdot (a_g / g) \tag{13}$$

$$K_v = 0.5K_h \tag{14}$$

The analyses have been performed parametrically considering three different friction angles φ' (i.e., 15°, 30° and 45°) and changing the slope inclination β from 1° to φ'. For each combination of φ' and β the following parameters were computed:

1) the static safety factor SF;
2) the pseudostatic safety factor according to the D.M. 1996 for the old three seismic categories in which the Italian territory was subdivided before March 2003.
3) the pseudostatic safety factor according to the EC-8, considering the 9 different values of ground acceleration (obtained combining S, S_T and a_g) characterizing the 4 seismic zones in which the OPCM 3274 nowadays classifies the Italian territory.

Comparing the pseudostatic safety factors computed according to the D.M. 1996 and the EC-8 for homogeneous seismic zones (for example, the 1st seismic category of the pre-existing D.M. 1996 and Zone 1 of the new classification) a huge discrepancy in the results obtained can be observed in Fig 2. This could be attributed to the quite different values in the magnitude of the horizontal pseudostatic force: the D.M. 1996 considers a horizontal force equal to 0.1W in a 1st category seismic zone while the OPCM 3274 provides horizontal pseudostatic forces of magnitude between 0.175W and 0.33W for seismic Zone 1. Further, the addition of the vertical pseudostatic force in the latter case contributes to exasperate the difference. In other words any artificial slope designed in the past in Italy, nowadays is no longer verified by applying EC-8 with the ground accelerations provided by OPCM 3274.

In Fig 2 the static and pseudostatic safety factors are plotted as functions of the difference (φ'-β) for a soil with friction angle φ'=30° and for the most severe seismic zone (the Ist category according to D.M. 1996 and Zone 1 according to the OPCM 3274).

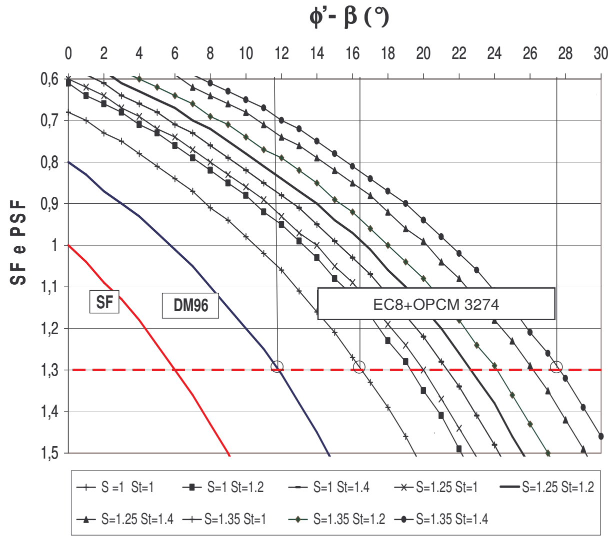

Fig 2: Pseudostatic analysis (φ'=30°): static and pseudostatic safety factors according to the D.M. 1996 and the EC-8 combined to the OPCM 3274 for seismic Zone 1.

It could be observed that if a safety factor equal to 1.3 is required for slope stability, when applying the EC-8 in conjunction to the OPCM 3274, higher (φ'-β) values are required, that is to say, lower slope inclinations β (between 13° and 3°), well below the value required by the D.M. 1996 (β=18°).

PSEUDODYNAMIC ANALYSIS

For the pseudo-dynamic analyses, the main accelerograms recorded during the 1980 Irpinia-Lucania earthquake have been adopted as input motions (Bagnoli Irpino, Brienza, Calitri, Mercato San Severino, Torre del Greco and Sturno).

The horizontal component of each accelerogram has been scaled in magnitude in order to obtain the 36 PGA values established for the 4 seismic zones up to a maximum peak ground acceleration equal to 0.66g. The accelerograms have been selected in such a way that their original PGA value was as close as possible to the maximum value required by the regulation. Since the vertical component of each accelerogram has also been considered, this was scaled consistently with the horizontal one.

As for the pseudostatic analyses, three different values of the soil friction angle φ' (i.e., 15°, 30° and 45°) were considered and the slope inclination β varied from 1° to φ'. As already found in previous studies (Simonelli, 1993; Simonelli and Fortunato, 1996) the final displacements computed applying the sliding block model depend significantly on the difference (φ'-β) while the influence of the single values of φ' and β is less relevant. Actually, the final displacement slightly increases with the values of φ'. Further, it changes in each seismic zone and within a unique zone it depends on the particular combination of both the soil and topography factors, respectively S and ST.

For the sake of simplicity in this study all displacements computed in each seismic zone have been adopted to obtain the so-called upper bound curve (Ambraseys and Menu, 1988) that represents the safest correlation between the maximum seismic-induced displacement and the ratio between the slope threshold acceleration and the maximum ground acceleration, i.e. the ratio Kc/Km. The displacement upper bound curve reflects both the maximum ground accelerations at the specific site and the features of the accelerogram time histories adopted in the displacement analysis. As a matter of fact, the upper bound curves should have regional validity. The upper bound curve shown in Fig 3, for example, refers to seismic Zone 1 of the Irpinia region since the accelerograms recorded during the 1980 Iprinia-Lucania earthquake have been adopted.

Similar curves have also been obtained for Zones 2, 3 and 4.

The upper bound curves may be adopted either to verify the displacement suffered by a slope during an earthquake, or to design artificial slopes and embankments.

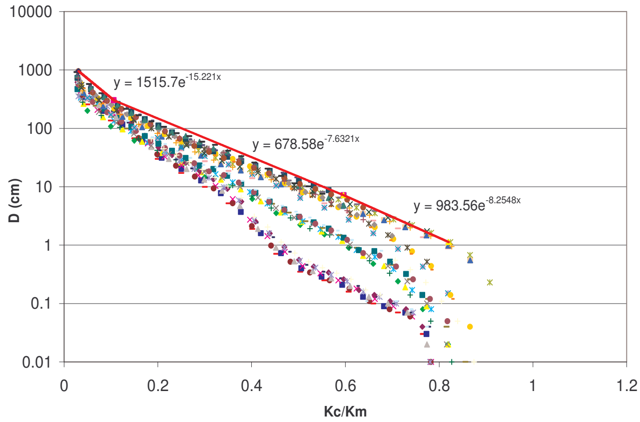

Fig 3: Upper bound curve for Zone 1 in the Irpinia region for a dry, infinite and incoherent slope (accelerograms scaled up to 0.66g)

To verify the stability of a dry, infinite and incoherent slope, it could be firstly determined the critical acceleration coefficient Kc according to eq. (5) and the site maximum expected acceleration (Km g) so that the threshold acceleration ratio Kc/Km could be determined; later from Fig 3 the maximum expected displacement in Zone 1 could be estimated. This value has to be compared to a maximum displacement, judged admissible for the particular case in hand.

To design an artificial slope, suitable design charts may be obtained from the upper bound curves. Fixing the displacement D, representing the maximum one allowed for the slope, the upper bound curve of Fig 3 could allow the deduction of the corresponding ratio Kc/Km. Hence, the threshold acceleration coefficient Kc and the slope inclination β can be easily determined.

In Fig 4, for example, the design chart relative to Zone 1 of the OPCM 3274 is shown. The upper plot shows the iso-displacement curves (D=1, 3, 5, 10, 30, 50 and 100 cm) as function of the difference (φ'-β) and of the maximum ground acceleration Amax (Amax=Km g). If the maximum ground acceleration at the site and the maximum admissible displacement D are known, the slope can be designed.

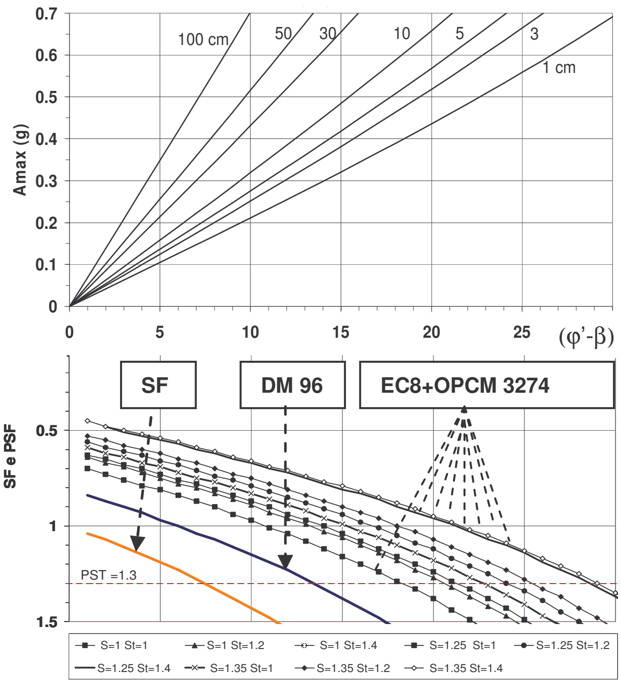

Fig 4: Design chart for artificial slopes in Zone 1 (OPCM 3274) of the Irpinia region (φ'=45°)

In the lower plot of Fig 4 the results of the pseudostatic application are shown as well, to allow an immediate comparison between the two approaches.

From the two plots of Fig 4 it could be observed that fixing a reasonable value of the admissible displacement (for example 10 cm) the design according to the pseudostatic approach of the EC-8 combined to the OPCM 3274 results strongly underdimensioned. Conversely, the design according to the D.M. 1996 seems more reasonable and better corresponding to the slope performance predicted by the pseudodynamic approach, especially when the ground accelerations at the site are less significant due to the favorable combination of site and topography conditions (lower values of S and S_T).

CONCLUSIONS

Slope stability analyses have been carried out according to EC-8 and the Italian pre-existing normative (D.M.96). The reference acceleration for defining the EC-8 seismic actions have been obtained from the recent Italian OPCM 3274 seismic zonation.

The comparisons among the analysis results have given rise to interesting conclusions:

- the D.M.96 and EC-8 pseudo-static methods provide very different designs, being the EC-8 design much more severe;
- a pseudo-dynamic analysis, based on the Newmark sliding-block model, with a proper set of accelerometric input motions fitting the requirements of EC-8 and OPCM 3274 normative, has confirmed that the EC-8 pseudo-static design is actually over-conservative;
- the difference between the pseudo-static design results of the D.M.96 and EC-8 essentially depends on the different evaluation of EC-8 seismic actions on the slope (correlated to the ground acceleration expected for a severe earthquake).

In conclusion, the present EC-8 pseudo-static method for slopes, together with the ground acceleration values of the OPCM 3274 Italian seismic zonation, appears to be inapplicable. An effective design can be achieved by more advanced dynamic analyses, with a suitable accelerometric representation of the seismic motion, as suggested by EC-8.

On the other hand, since the application of pseudo-static methods is well consolidated in the engineering practice, it would be very useful to save the EC-8 pseudo-static approach. At this aim, it would be necessary to better calibrate the correlation between the ground accelerations and the pseudo-static actions on the slope, by the introduction of proper model coefficient values, which have to effectively convert the real and complex dynamic action into a pseudo-static force, or, in alternative, to define different partial safety factor values for verifying the slope under the severe design earthquakes.

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