

ON SEISMIC SLOPE DISPLACEMENT ESTIMATION METHODS, PROCEDURES, COMPARISON, AND APPLICATION

MÉTODOS DE PREDICCIÓN DE DESPLAZAMIENTOS SÍSMICOS, PROCEDIMIENTO, COMPARACIÓN Y APLICACIÓN

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ABSTRACT

The methodology in the seismic design of slopes has evolved with technological advancement and the development of geotechnical engineering. Since methods with great limitations such as pseudo-static analysis to rigorous methods that require a lot of information for a better understanding of the behavior of the soil such as the dynamic analysis.

This article develops the procedure, comparison, and application of methods for estimating seismic displacements, which are the Newmark [1], Sarma [2], Makdisi & Seed [3] and Bray, Macedo & Travararou [4]. Each of these methods considering the criteria of each one to obtain permanent displacements, such as yield acceleration, degraded period, spectral acceleration, magnitude, etc.

As an applicative case, a rockfill dam and core central 50 m high placed in sandstone strata and moraine deposits interspersed with shale intrusions is shown, as seismic scenarios the Lima 1974 earthquake, the Attic 2001 earthquake and the earthquake of Pisco 2007, considering both NS and EW directions. Likewise, the response spectrum on the base of the failure surface, resulting from a nonlinear seismic response analysis from 3 columns in the dam, is considered as information. The methods of Newmark [1], Sarma [2], Makdisi & Seed [3] and Bray, Macedo & Travararou [4] were applied, obtaining deformation results between 1 to 30 cm that according to their order of magnitude represent a stable condition for the dam.

Keywords: earthquake-induced simplified displacement methods, dynamic analysis, measure stability and earth dam.

RESUMEN

La metodología en el diseño sísmico de taludes ha evolucionado con el avance tecnológico y el desarrollo de la ingeniería geotécnica. Desde métodos con grandes limitaciones como el análisis pseudoestático hasta métodos rigurosos que requieren mucha información para una mejor comprensión del comportamiento del suelo como el análisis dinámico.

En este artículo se desarrolla el procedimiento, comparación y aplicación de los métodos para estimar los desplazamientos sísmicos, que son el Newmark [1], Sarma [2], Makdisi & Seed [3] and Bray, Macedo & Travararou [4]. Cada uno de estos métodos considera los criterios característicos para obtener desplazamientos permanentes, tales como aceleración de fluencia, periodo degradado, aceleración espectral, magnitud, etc.

Como caso aplicativo, se muestra una presa de enrocado y núcleo central de 50 m de altura emplazada en estratos de areniscas y depósitos morrénicos intercalados con intrusiones de lutitas, como escenarios sísmicos se utilizaron el terremoto de Lima 1974, el terremoto de Atico 2001 y el terremoto de Pisco 2007, considerando las direcciones NS y EW. Asimismo, se considera como información el espectro de respuesta en la base de la superficie de falla, resultante de un análisis de respuesta sísmica no lineal de 3 columnas de la presa. Se aplicaron los métodos de Newmark [1], Sarma [2], Makdisi & Seed [3] and Bray, Macedo & Travararou [4], obteniéndose resultados de deformación entre 1 y 30 cm que de acuerdo a su orden de magnitud representan una condición estable para la presa.

Palabras clave: Métodos de desplazamiento simplificado inducido por sismo, Análisis dinámico, Medida de estabilidad, Presa de tierra.

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1. INTRODUCCIÓN

The significance of methods for estimating seismic displacements is due to the potential occurrence of large landslides triggered by earthquakes of certain magnitudes, as noted by Keefer [5] "Moderate to large earthquakes can cause large landslides at great distances from the epicenter, with distances up to 500 km, depending on their magnitude".

Kramer [6] provides a comprehensive explanation of the effects of seismic movements on slopes in his book. Seismic movements generate significant horizontal and vertical dynamic stresses, producing shear and normal dynamic stresses along potential failure surfaces within the slope.

Dynamic shear stresses can exceed the available shear strength of the soil and cause inertial instability on the slope when combined with previously existing static shear stresses. Numerous techniques have been proposed for the analysis of inertial instability, differing in the precision with which seismic motion and dynamic slope response are represented. The

subsequent sections describe several common approaches to inertial instability analysis. Pseudo-static analysis, the first approach, calculates a factor of safety along the slope failure surface under seismic conditions, like how static limit equilibrium analyzes factors of safety against static slope failure. All other approaches attempt to assess permanent slope displacements caused by seismic shocks [6].

The importance of the methods for estimating seismic displacements lies in the large landslides that can occur due to earthquakes of a certain magnitude, from the results of Keefer [5]: "The earthquakes of moderate to large magnitude can trigger large landslides at great distances from the epicenter such as 500 km, this depending on its magnitude".

Due to the different existing methods, it is necessary to evaluate the application of each of these; Fig. 1 shows a diagram of the methods available to analyze a slope in a seismic condition.

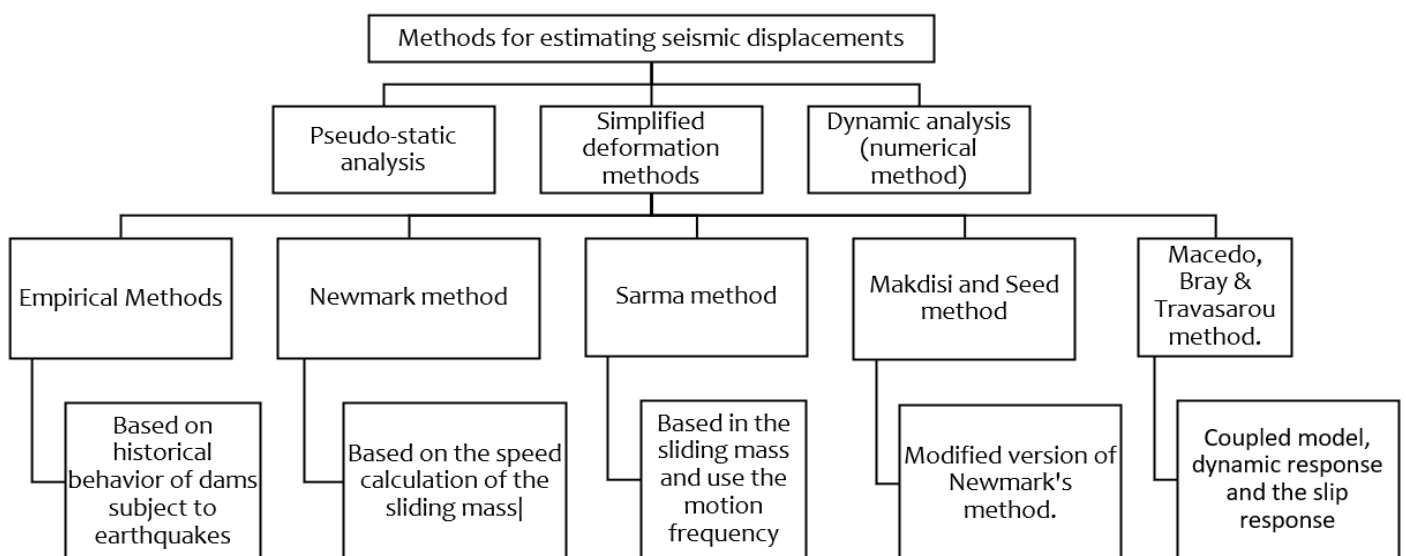


Fig. 1. Representative diagram with some of the methodologies used to represent the seismic condition.

2. BACKGROUND

2.1 RIGID BLOCK MODEL

The rigid block model was proposed by Newmark in 1965, based on the simplification of the sliding surface by that of an infinitely rigid block that slides on a flat surface whose movement begins when the accelerations induced by earthquakes exceed the yield acceleration, k_y .

During the movement of the sliding block the speed of the support surface and the sliding mass are different, the movement (sliding) will continue until the following 2 conditions are met:

- When the accelerations no longer exceed the yield acceleration, k_y
- The speed of the sliding mass is equal to the speed of the underlying ground or bearing surface.

During each interval of movement of the block, the permanent displacements accumulate, and these will be determined with the double integration method, which consists of obtaining the speed of the block from the integration of the acceleration that exceeds

the yield acceleration, k_y , as a function of time and then obtain the displacements by integrating said speed as a function of time. The Fig. 2 illustrates the simplification to rigid block model:

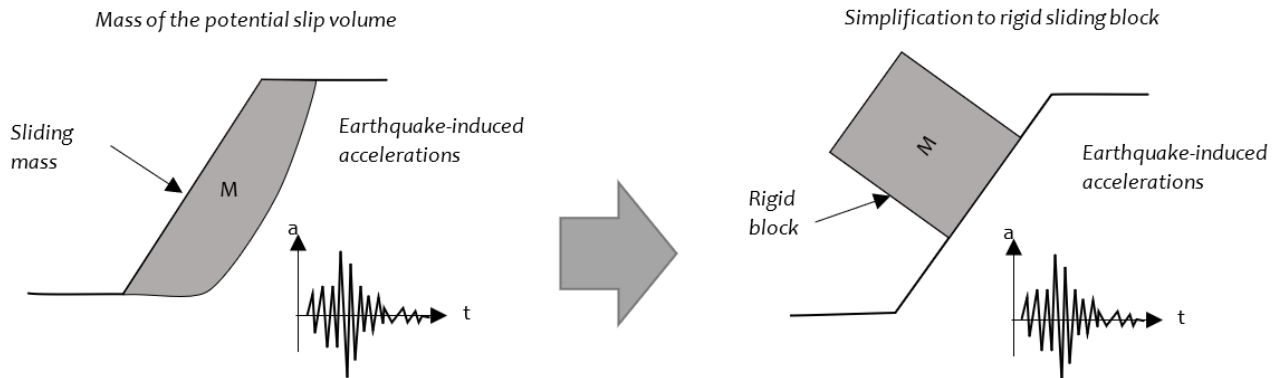


Fig. 2. Representative diagram of the mass simplification of the potential sliding volume to a rigid sliding block.

The theoretical assumptions presented by the rigid block model are described below based on what Murphy [7] mentions in his publication:

- The sliding mass is assumed to be a non-conforming or non-deformable rigid block (acceleration of the sliding mass is equal to the acceleration of the bearing surface while “ $a < k_y$ ”, where “ a ” refers to the acceleration of the sliding mass)
- The performance behavior of the material is non-elastic, perfectly plastic (implicit in the use of k_y).
- The displacements are assumed to occur along a single well-defined slip surface (typically the critical pseudo-static surface of Limit equilibrium method, k_y -associated surface)
- The material does not suffer loss of strength because of shocks.
- The accelerations and the corresponding inertial forces act in the direction of the initial motion at the center of gravity of the sliding mass.

2.2 DECOUPLED MODEL

The decoupled model was proposed by Makdisi and Seed [3], based on the concepts of slip and permanent deformation proposed by Newmark in 1965, but modified by considering the dynamic

response of the sliding surface. The dynamic response of this model is the result of the development of codes to perform a finite element analysis. The decoupled model is made up of 2 parts, hence its name:

The dynamic response analysis, which consists of obtaining the dynamic response of the sliding mass as a function of depth, this calculation can be done with one-dimensional or two-dimensional systems, resulting in an average of the accelerations acting on the sliding mass as a function of the time known as horizontal equivalent acceleration, AEH (t).

The sliding response analysis is performed with the double integration of the horizontal equivalent acceleration.

The theoretical assumptions presented by the decoupled model corresponding to the dynamic response analysis are described below based on what Murphy [7] mentions in his publication:

Sliding mass is modeled as a compliant block (if there is a dynamic response).

The dynamic response of the slipping mass is not influenced by the slip that occurs, as these two

behaviors are modeled by separate analyzes (the slip surface is not present for the dynamic response analysis).

The nonlinear stress-strain hysteretic behavior of the material is modeled in an approximate way (most commonly linear-equivalent based on iterations).

Seismic waves approximate horizontally polarized and vertically propagating shear waves.

And the theoretical assumptions presented by the decoupled model corresponding to the sliding response analysis are the same as the rigid block mentioned above.

2.3 COUPLED MODEL

The coupled model cannot be attributed to a single researcher since that its use has been proportional to the evolution of numerical codes and the greater computing power available. The coupled analysis is used in sophisticated numerical codes such as FLAC, OpenSees and PLAXIS, although there are also simplified methods based on equations (e.g., Bray and Travasarou [8]). The coupled model manages to represent the interaction between the dynamic response and the slip response that the decoupled model could not relate to.

As can be seen in Fig 3, there are various models for the mechanism of earthquake-induced deformation.

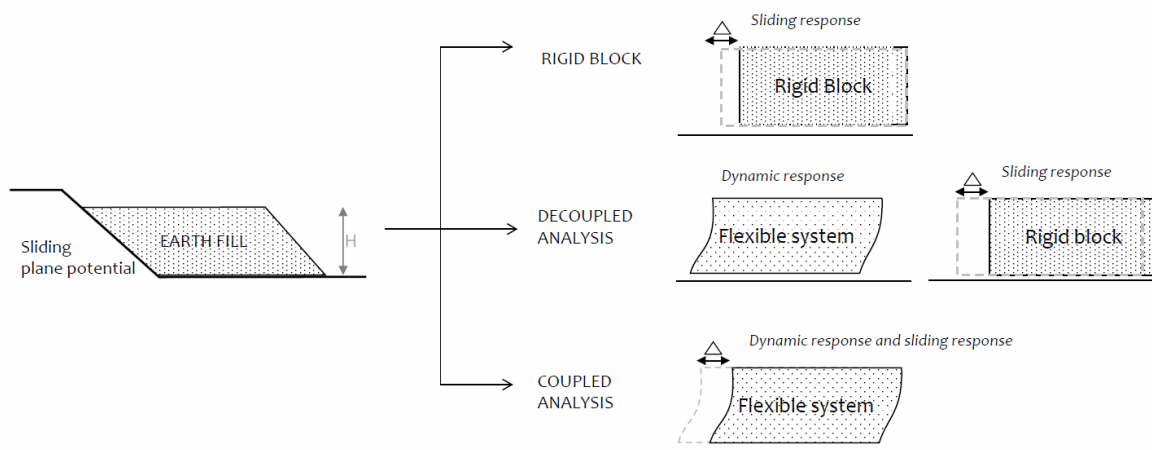


Fig. 3. Diagram of the rigid uncoupled and coupled block models. Modified from: Bray & Travasarou (2007)

3. METHODOLOGY

3.1 NEWMARK METHOD 1965

1. Acceleration record acquisition: The seismic accelerations record is collected for the three earthquakes mentioned (Atico 2001, Lima 1974 and Pisco 2007) in the NS and EW directions. The accelerations at the base of the slope failure surface downstream of the dam are obtained.
2. Evaluation of the threshold acceleration (creep acceleration): The value of the creep acceleration (k_y) is determined for the specific case of the dam under study. The creep acceleration has been obtained from a pseudo-static analysis with a factor of safety, $SF=1$, in this case the value is $0.28 g$.

This acceleration represents the available soil resistance that must be overcome for sliding to occur.

3. Integration of accelerations: The mathematical integration method is used to obtain the velocities; the integration is performed when the acceleration recorded at the base of the slope failure surface exceeds the value of the creep acceleration.
4. Displacement calculation: Integration is applied again to obtain the total displacement of each of the analyzed columns of the dam.

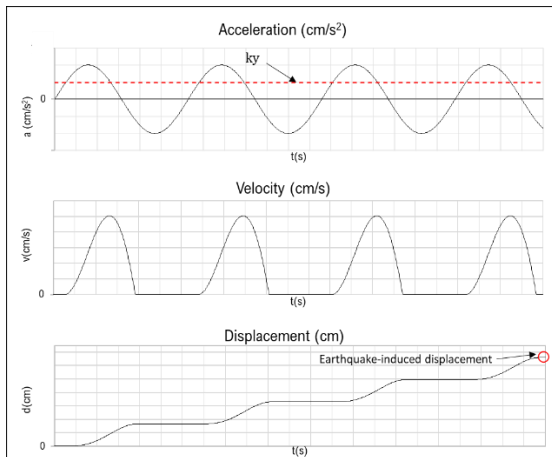


Fig. 4. Double integration scheme following Newmark 1965 algorithm.

3.2 SARMA METHOD 1975

1. Definition of initial parameters: The fundamental period, peak acceleration at the surface and soil depth are determined. These parameters are necessary for the calculation of earthquake-induced deformations.
2. Calculation of creep acceleration (k_y): Using the information provided, the value of creep acceleration (k_y) is determined. This acceleration represents the available strength of the soil and is used to evaluate the resulting deformation.
3. Obtaining earthquake-induced displacements: The algorithm and the figure provided (Fig. 5) are used to calculate the earthquake-induced displacements. Note that Sarma's method considers the frequency content of the ground motion, which distinguishes it from other simplified methods.
4. Verification of the allowable displacements: The displacements obtained are compared with the established allowable displacements. According to the literature, it is mentioned that the allowable displacements should be less than 1 meter ($\Delta < 1\text{m}$).

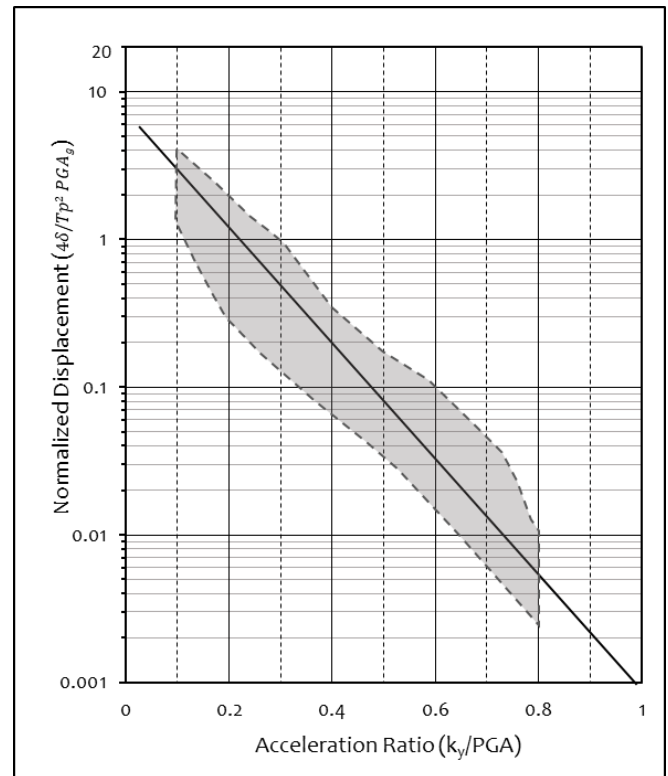


Fig. 5. Variation of dimensionless displacement with K_c/K_m . [9]

3.3 MAKDISI & SEED METHOD 1978

1. Calculation of creep acceleration (yield acceleration, k_y): Using the available data, the value of creep acceleration (k_y) is determined. This acceleration represents the available resistance of the soil and is an important parameter in the calculation of earthquake-induced deformations.
2. Calculation \ddot{u}_{max} (maximum Acceleration): Using earthquake data and dam geometry, and a nonlinear seismic response analysis, the maximum acceleration at the dam crest is determined.
3. Use of the 1st abacus (see Fig. 6): The 1st abacus is used to determine the value of k_{max}/\ddot{u}_{max} (coefficient that relates the available resistance to the maximum acceleration at the crest of the dam).
4. Use of the 2nd abacus (see Fig. 6): Using the values of k_y , k_{max}/\ddot{u}_{max} and the magnitude of the moment of the earthquake (M_w), the 2nd abacus is used to determine the earthquake-induced displacements.

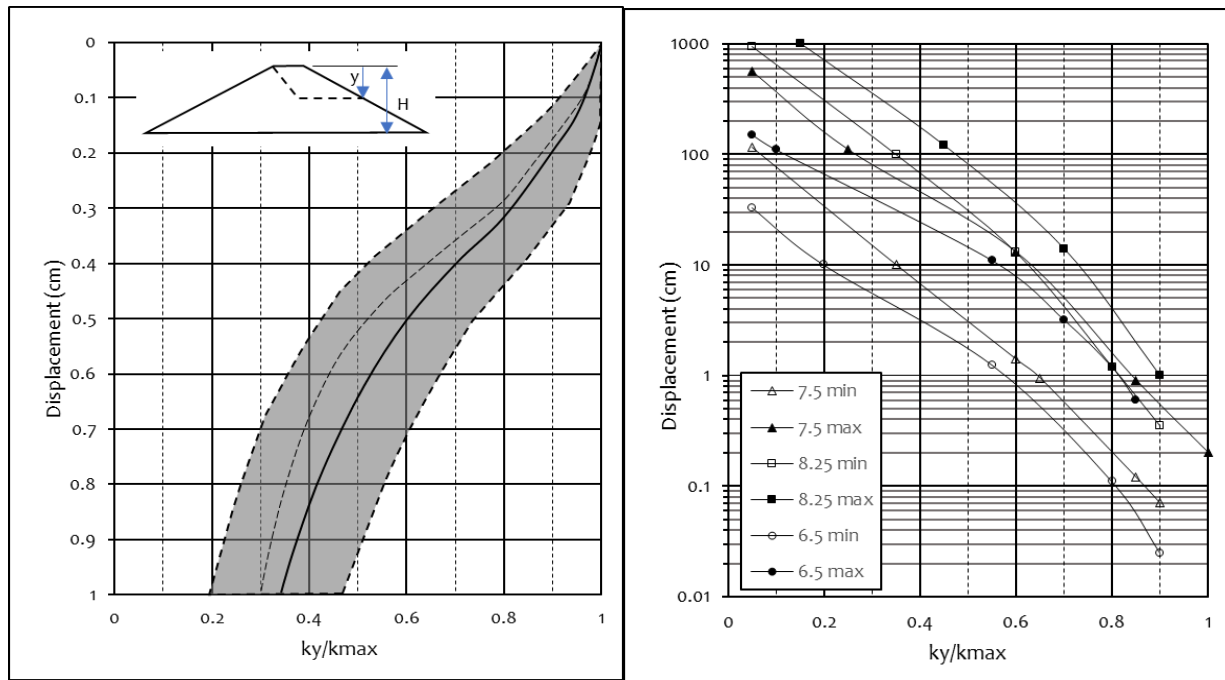


Fig. 6. Scheme indicating the use of the abaci raised in the method of Makdisi & Seed 1978. [8]

3.4 METHOD OF BRAY MACEDO AND TRAVASAROU 2018

Determination of the necessary variables: Using the input parameters provided (k_y , T_s , $1.5 * T_s$, M_w , $S_a(1.5T_s)$), the values corresponding to each variable are determined.

Calculation of the probability of zero displacements ($P(D = 0)$): Depending on the value of the fundamental period T_s , the following formulations are applied to calculate the probability that no displacement will occur:

$$1. \quad T_s \leq 0.7s$$

$$P(D = 0) = 1 - \Phi \left(-2.64 - 3.20 * \ln(k_y) - 0.17 * \ln(k_y)^2 - 0.49 * T_s * \ln(k_y) + 2.09 * T_s + 2.91 * \ln(S_a(1.5T_s)) \right)$$

$$2. \quad T_s > 0.7s$$

$$P(D = 0) = 1 - \Phi \left(-3.53 - 4.78 * \ln(k_y) - 0.34 * \ln(k_y)^2 - 0.30 * T_s * \ln(k_y) - 0.67 * T_s + 2.66 * \ln(S_a(1.5T_s)) \right)$$

Where ϕ represents the cumulative distribution function of a standard normal distribution.

Estimation of non-zero seismic displacement (D): Using the coefficients a_1 , a_2 and a_3 provided in the formulation, the natural logarithm of the estimated displacement ($\ln(D)$) is calculated. The complete formulation is shown below:

$$\ln(D) = a_1 - 3.353 * \ln(k_y) - 0.390 * (\ln(k_y))^2 + 0.538 * \ln(k_y) * \ln(S_a(1.5T_s)) + 3.060 * \ln(S_a(1.5T_s)) - 0.225 * \ln(S_a(1.5T_s))^2 + a_2 * T_s + a_3 * (T_s)^2 * (0.55M_w)$$

Where the values of a_1 , a_2 and a_3 are provided in the text, depending on the condition $10sTs \geq 0$ or $10sTs < 0$.

$a_1 = -6,896$; $a_2 = 3,081$; $a_3 = -0.803$ for $10sTs \geq 0$.
 $a_1 = -5,864$; $a_2 = -9,421$; $a_3 = 0.0$ for $10sTs < 0$.

The method of Bray, Macedo, and Travararou [4] is a simplified approach for estimating deformations in dams by considering the sliding mass with a coupled model. This method integrates the dynamic response and sliding response, specifically focusing on subduction earthquakes. The input variables required for the analysis include the yield acceleration (k_y), the fundamental initial period (T_s), the degraded period ($1.5T_s$), the moment magnitude (M_w), and the spectral acceleration ($S_a(1.5T_s)$). The method provides the displacement along with a probability of non-displacement as the result, which can be considered as a mixed variable.

It is important to follow the exact formulations and make sure you use the correct values for each input parameter. The application of the method of Bray, Macedo and Travararou [4] will require an analysis of seismic response and spectral adjustment based on the specific data of the rockfill dam with central core, using the acceleration records of the earthquakes (Lima 1974, Atico 2001 and Pisco 2007).

3.5 APPLICABLE CASES: ROCKFILL DAM WITH CENTRAL CORE

There is the following rockfill dam with a central core located on sandstone strata and moraine deposits interspersed with 50 m high shale intrusions, the spectral adjustment and response analysis were developed in the 3 soil columns observed in Fig. 7, which also has the following basic data of the dam:

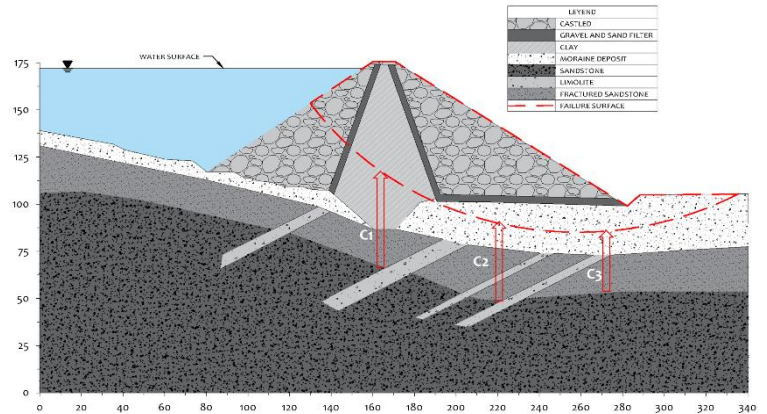
There is the following rockfill dam with a central core located on sandstone strata and moraine deposits interspersed with shale intrusions 50 m high, the spectral adjustment and response analysis were developed in the 3 soil columns observed in Fig. 8, it also has the following basic data of each of the analyzed columns of the dam:

Data:

- Earthquakes used: Lima 1974, from the IGP; Attic 2001, from CISMID; Pisco 2007, from CISMID
- M_w = 7.9 (Pisco), 8.4 (Atico) y 8.1 (Lima)
- H = 50 m

- k_y = 0.28 g
- $V_{s_{prom}}$ = 642 m / s
- T_s = 0.311 s
- $T_{s_{deg}}$ = 0.467 s

All methods were applied for this case:



4. ANALYSIS OF RESULTS

For the analysis of the results, the acceleration response spectrum is shown in Fig. 8 and the induced seismic displacements in Fig. 9.

It is important to observe the amplification of the spectral acceleration for the degraded period ($T_{s_{deg}} = 0.467$ s) as shown in Fig. 8, column 1 has a greater amplification than column 2 and 3, this is reflected in the displacements obtained in the method of Bray, Macedo & Travararou [4].

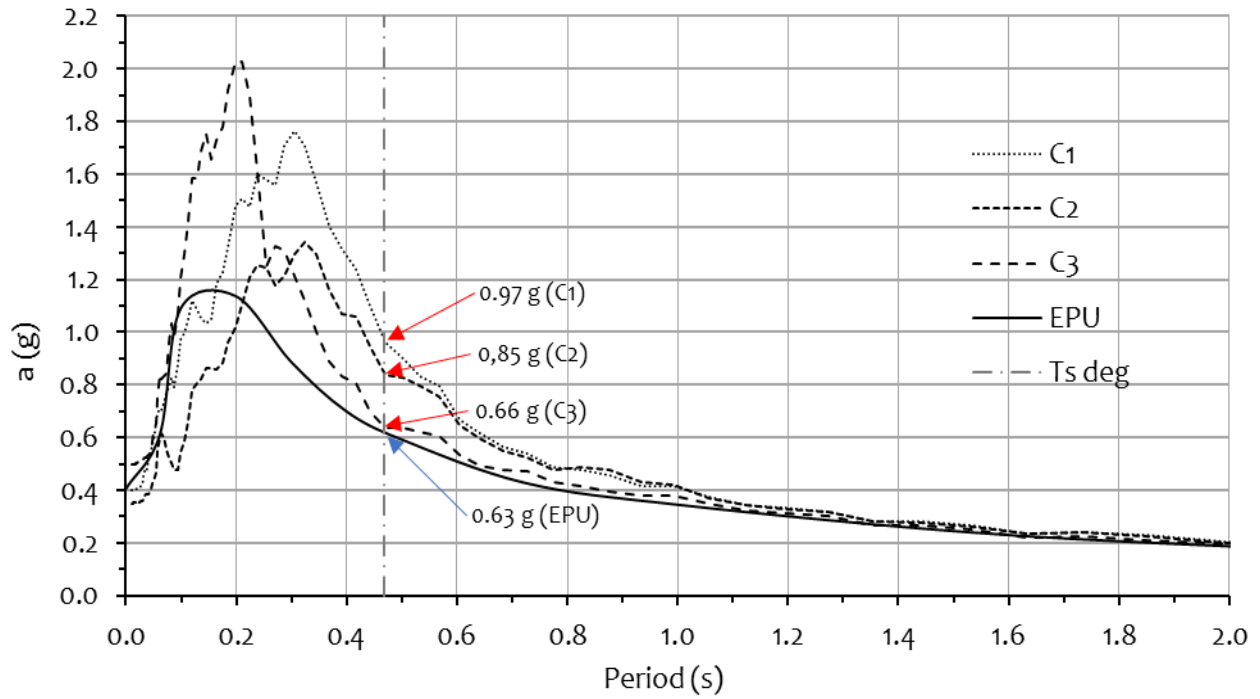


Fig. 8. Acceleration spectra of the seismic response at the top of the 3 analyzed columns.

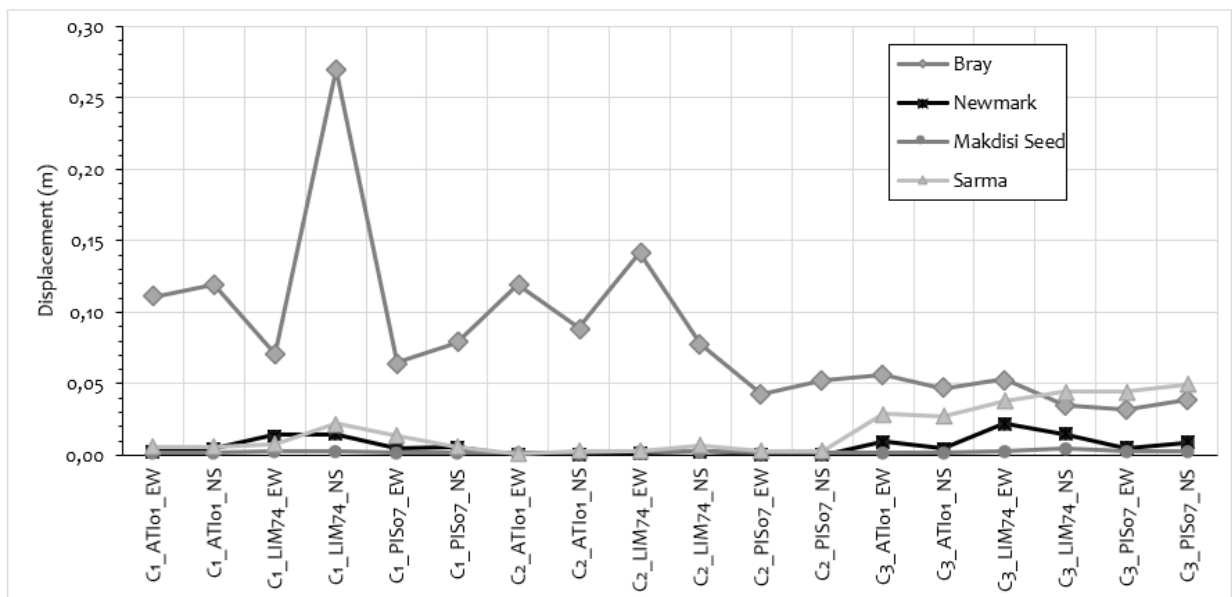


Fig. 9. Resulting displacements for each method.

Where according to its nomenclature:

- C1, C2 and C3 : Column analysed.
- EW and NS : Earthquake in East-West and North-South directions, respectively.
- AT101, LIM74 and PIS07 : Earthquake of Atico 2001, of Lima 1974 and of Pisco 2007, respectively.

The following table shows the maximum displacements obtained by the four simplified methods for each analysis column.

TABLE I
PGA obtained in each column for three earthquakes.

	Pisco 2007			Atico 2001			Lima 1974		
	C1	C2	C3	C1	C2	C3	C1	C2	C3
PGA	0.42	0.35	0.52	0.38	0.35	0.47	0.46	0.39	0.51

TABLE II
Displacements obtained by the four applied methods for three earthquakes.

Method	Maximum displacements (cm)								
	Pisco 2007			Atico 2001			Lima 1974		
	C1	C2	C3	C1	C2	C3	C1	C2	C3
Newmark 1965	0.49	0.05	0.95	1.45	0.29	1.47	0.57	0.06	0.92
Sarma 1975	1.33	0.32	4.96	0.60	0.32	2.87	2.20	0.70	4.43
Makdisi & Seed 1978	0.20	0.20	0.20	0.30	0.30	0.50	0.20	0.20	0.30
Bray, Macedo and Travararou 2018	11.90	11.90	5.60	27.00	14.20	5.30	7.90	5.20	3.90

The displacements obtained in column 3 by the Sarma [2] method are higher because the peak ground acceleration (PGA) has higher values, this parameter being significant for this particular method. (See TABLE I).

The maximum displacements were observed with the method of Bray, Macedo and Travararou [4], with displacements of approximately 3.90 to 27.00 centimeters, while the minimum displacements occurred with both the methods of [1], [2], [3]. (See TABLA II)

It is observed that the seismic induced displacements obtained by the [1], [2], [3] methods are in the range of 0 to 2 cm (except Sarma's method in column 3) which indicates displacements that are not significant for the dimensions of the dam, this is explained according to the fact that the seismic demand does not exceed the creep acceleration, which represents

the dynamic resistance in these two methods. (See TABLE II)

The Makdisi & Seed [2] method does not show variation between columns, this may be due to the use of abacuses, since it is a method that considers fewer factors, while the other methods do show variation between one column and another. (See TABLE II)

CONCLUSIONS

Based on the work carried out, the following conclusions and recommendations are presented:

- According to the results of the application example, it is concluded that all the deformations presented are in the range of 0.1 - 30 cm, which indicates an acceptable deformation for the stability of a dam.

- It is recommended to limit the use of the Newmark 1965 method to fault surfaces with shallow depth and composed of rigid materials because the dynamic response of this sliding mass intervenes in the final deformation results, however, if we take a failure surface with the characteristics mentioned can approximate its behaviour to that of a rigid block as indicated by Newmark.
- The use of the method of Makdisi & Seed [3] should be taken with care because the abacus that indicate the dynamic response and the response to sliding have been generated from limited cases of dams, this could be the reason why the values obtained with this method are similar in the three columns for the three cases, today there is much more information and to want to use This methodology should update the data.
- The earth dam studied presents varied materials with different dynamic behaviors, which generates that the displacements obtained by the [1], [2], [3] methods are not as close to a more rigorous method such as Bray, which considers the dynamic response in a coupled manner.
- It is convenient to perform displacement analysis with the methods of [2] and [4] since they usually present a more conservative result.
- The use of the Bray, Macedo and Travasarou [4] method is quite acceptable because it considers within its equations the use of more variables such as the fundamental period of the slippery mass or the spectral acceleration on the failure surface that implicitly requires an analysis response seismic.
- The use of the method of Bray, Macedo and Travasarou [4] is an extremely reliable method applicable to our seismic zone, so its use is recommended in terms of simplified methods of earthquake-induced deformations.

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