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MODIFIED NEWMARK APPROACH FOR EVALUATION OF EARTHQUAKE–INDUCED DISPLACEMENT OF EARTH DAM-APPLYING FOR RE-DIVISION OF SLIDING MASS

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ABSTRACT: The conventional Newmark sliding block approach for evaluating the earthquake-induced displacement of earth dams is widely used in practice. However, the change in the position of the sliding mass with time when a slip occurs is not taken into account in the conventional Newmark approach when calculating the seismic displacement during an earthquake. Thus, a modified Newmark analysis is presented here in order to consider the influence of the changing position of the sliding mass on the estimated seismic displacement of an earth dam by re-dividing the sliding mass. A comparison of the results of the conventional and the modified Newmark approaches shows that ignoring the change in the sliding mass position over time can lead to the overestimation of the sliding displacement, especially if the Fellenius method, a less rigorous method, is used for evaluating the yield seismic intensity. In this study, the modified Newmark approach, using a relatively easy method among strict methods (simplified Bishop method), leads to a more realistic assessment of the permanent displacement in seismic slope stability analyses.

Keywords: Conventional Newmark sliding block, Simplified Bishop method, Earthquake-induced displacement, Earth dam, Re-dividing sliding mass

1. INTRODUCTION

The analysis of seismic slope stability is a challenging geotechnical problem, attracting tremendous interest amongst researchers. Over the past century, awareness of the adverse effects of earthquakes on earth dams has increased. Along with this is an increase in society's demand for ensuring the safety of these structures during potential earthquakes in the future. The factor of safety, F_s, is a "stability index" calculated by the ratio of the resisting moment/force and the driving moment/force of a soil mass that follows along a potential slip surface in a limit equilibrium state. It is frequently used to determine whether a slope is stable or unstable in the most popular seismic design scheme of earth dams. However, that approach does not reveal what happens after the equilibrium is exceeded (i.e., F_s is less than 1.0), so the consequences of instability or even the likelihood of failure cannot be judged. The performance level of a slope is best evaluated through an assessment of the potential for seismic permanent displacements [1-3]. Hence, displacement is a more appropriate criterion for designing earth dams under earthquake loading conditions than the factor of safety. Thus, analyses of the seismic permanent displacements of earth dams have become more important and necessary in designing new dams as well as in evaluating the earthquake response of existing dams.

Newmark [4] proposed a simple approach for evaluating the potential deformation of earth dams and embankments due to earthquake shaking based on a rigid slide block above the slippage surface, known as the conventional Newmark sliding block approach (hereinafter referred to as the conventional Newmark approach). Newmark argued that the block begins to slip along the plane when the seismic acceleration exceeds the yield acceleration. Due to its simplicity and efficiency, the conventional Newmark approach has been widely applied in practice. This method is employed in the design code of dams in Japan [5] for performance verification against level 2 earthquake motion. The permanent seismic displacement of the circular rigid sliding mass is calculated by the double integration of the angular acceleration based on a given recorded acceleration time history when the seismic acceleration exceeds the yield acceleration. The procedure requires that the value of the yield acceleration or yield seismic intensity be determined for the potential failure surface using conventional limit equilibrium methods. The ordinary method of slices, or Fellenius method, is commonly used in the conventional Newmark approach to calculate the factor of safety as well as the yield seismic intensity. However, this method ignores the forces between the slices needed to facilitate the calculation. When compared to the rigorous methods, which take into account the forces between the slices, the factor of safety of the Fellenius method is smaller [6].

Therefore, it can be predicted that the amount of displacement calculated by the conventional Newmark approach will be larger than that calculated by a strict method.

As is known, the acceleration time history data is the acceleration data measured at certain time intervals of an earthquake. At any given time interval, when the seismic acceleration exceeds the yield acceleration, the sliding mass will slip. However, in the conventional Newmark approach used at present, the change in the position of the sliding mass at that interval is not considered much in the analysis. Therefore, the fixed sliding mass position in the conventional Newmark approach may lead to unreliable estimations of seismic slope deformations. Nishimura [7] considered the changing of the sliding mass position through the re-division of the sliding mass as the sliding mass moves at the time steps of the acceleration time history data. However, he also used the Fellenius method to calculate the earthquake-induced permanent displacement.

In this study, therefore, a modified Newmark approach is proposed to evaluate the seismic displacement of an earth dam based on the changing position of the sliding mass over time. In the proposed procedure, the change in the sliding mass position is taken into account by re-dividing the slip mass in the time step of the slip occurrence. Moreover, a relatively easy method among the strict methods is used, namely, the simplified Bishop method, to evaluate the yield seismic intensity. Seismic displacements are evaluated and compared for the Fellenius and simplified Bishop methods in both conventional and modified Newmark approaches.

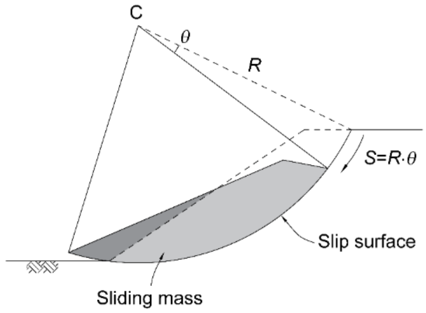
2. THE NEWMARK METHODOLOGY

2.1 Rotational Permanent Displacement

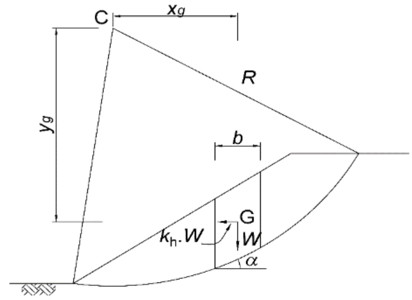
When evaluating a seismic stability analysis or Newmark analysis, the shape of the slip surface is a curve that is often assumed as a circle by many researchers, including Fellenius and Bishop [8,9]. Accordingly, the rigid mass of the conventional Newmark analysis is a circular mass that rotates relative to the failure surface during shaking. The rotational permanent displacement of the circular rigid sliding mass is computed through the integration of the equation of motion.

Figure 1 shows a calculation model of a slope subjected to a time history of acceleration. The equation of motion of the sliding mass resting on the critical circular slip surface is as follows [10,11]:

$$-J \cdot \ddot{\theta} + M_{\mathrm{DW}} + k_{\mathrm{h}} \cdot M_{\mathrm{DK}} - M_{\mathrm{RW}} - k_{\mathrm{h}} \cdot M_{\mathrm{RK}} - M_{\mathrm{RC}} = 0 \quad (1)$$



a) Schematic diagram of rotational slide



b) Definition of symbols

Fig. 1 Newmark sliding block analysis

where θ is the rotation angle, J is the moment of inertia, M_{DW} is the driving moment due to the self-weight, M_{DK} is the standard driving moment due to the seismic inertial force, M_{RW} is the resisting moment due to the self-weight, M_{RK} is the standard resisting moment due to seismic inertial force, M_{RC} is the resisting moment due to the adhesive force on the slip surface, and k_{h} is the horizontal seismic intensity. Although vertical seismic acceleration is also possible, only horizontal seismic acceleration is given in this study.
In addition, each term can be expressed by the following equation:

$$M_{RW} = R\sum(W - b \cdot u)\cos\alpha \cdot \tan\varphi \quad (2)$$

$$M_{RK} = R\sum W \cdot \sin\alpha \cdot \tan\varphi \quad (3)$$

$$M_{RC} = R\sum c \cdot l \quad (4)$$

$$M_{DW} = \sum W \cdot x_g \quad (5)$$

$$M_{DK} = \sum W \cdot y_g \quad (6)$$

where W is the weight of the slice at the slice centroid, c is the cohesion of the soil, φ is the soil friction angle, b is the width of the slice, l is the length of the slip surface, α is the angle of the base of the slice and the horizontal, u is the pore water pressure, and x_{g} and y_{g} are the horizontal and vertical distances between the slice centroid and the center of the circular slip surface.

The angular acceleration of the sliding mass, $\ddot{\boldsymbol{\theta}}$, is expressed by Eq. (7):

$$\ddot{\theta} = \frac{(k_h - k_y)(M_{DK} - M_{RK})}{J} \quad (7)$$

$$k_y = \frac{M_{RW} + M_{RC} - M_{DW}}{M_{DK} - M_{RK}} \quad (8)$$

where k_y is the yield seismic intensity obtained from horizontal seismic intensity k_h when the factor of safety against rotational displacement F_s is equal to unity.

Factor of safety F_s in the ordinary method of slices, or the Fellenius method, is given by the ratio of resisting moment M_R and driving moment M_D, as

$$F_S = \frac{M_R}{M_D} = \frac{R\Sigma\left[C \cdot l + (W \cdot \cos\alpha - u \cdot l - k_h \cdot W \cdot \sin\alpha)\tan\varphi\right]}{\Sigma\left[W \cdot x_g + k_h \cdot W \cdot y_g\right]} \quad (9)$$

By assigning unity to F_s, the equation can be rearranged in terms of the yield seismic intensity as

$$k_y = \frac{R\Sigma\left[C \cdot l + (W \cdot \cos\alpha - u \cdot l)\tan\varphi\right] - \Sigma W \cdot x_g}{\Sigma\left[W \cdot y_g + W \cdot \sin\alpha \cdot \tan\varphi\right]} \quad (10)$$

Since angular acceleration $\dot{\boldsymbol{\theta}}$ and rotation angle θ of the sliding mass are functions of time t, their time history can be obtained by numerical integration using the input seismic acceleration of the time interval, Δt [10-13]. In this study, the numerical integration was performed by the linear acceleration method using Eqs. (7), (11), and (12).

$$\dot{\theta}_{t+\Delta t} = \dot{\theta}_t + \frac{1}{2}(\ddot{\theta}_t + \ddot{\theta}_{t+\Delta t})\Delta t \quad (11)$$

$$\theta_{t+\Delta t} = \theta_t + \dot{\theta}_t \Delta t + \frac{1}{6}(2\ddot{\theta}_t + \ddot{\theta}_{t+\Delta t})\Delta t^2 \quad (12)$$

The rotational permanent displacement, S, is then computed from Eq. (13) with the radius of the circular slip surface, R, and the rotation angle, θ.

$$S = R \cdot \theta \quad (13)$$

The conventional Newmark analysis uses the ordinary method of slices, or the Fellenius method, to find the potential failure surface by calculating the factor of safety based on satisfying the force equilibrium equations. The ordinary method of slices is not an exact method because there are more unknowns than equilibrium equations. This requires that an assumption be made concerning the interslice forces, namely, that the interaction forces between adjacent slices are ignored. As a result, this method produces a conservative value that is lower than the actual factor of safety [6]. It is rational to assume that the method may yield a lower value than the actual yield seismic intensity. This leads to a huge result for the permanent displacement. Therefore, a more rigorous method will provide results closer to reality. For the rigorous methods, such as the Spencer and Morgenstern-Price methods, both force and moment equilibrium can be satisfied, but usually the analysis is more tedious, sometimes non-convergence problems are encountered, and the original formulation does not provide the flexibility to add earthquake loading to the existing static loads. Meanwhile, the simplified Bishop method (hereinafter referred to as the Bishop method) is a stricter method than the Fellenius method, in which normal interaction forces between adjacent slices are assumed to be collinear and the resultant interslice shear force is zero.

By considering horizontal seismic intensity k_h, the original formulation by Bishop [9] can be rewritten as

$$F_s^* = \frac{M_R}{M_D} = \frac{R\Sigma\left[\left\{c \cdot b + (W - b \cdot u)\tan\varphi\right\}/m_\alpha\right]}{\Sigma\left[W \cdot x_g + k_h \cdot W \cdot y_g\right]} \quad (14)$$

$$m_\alpha = \cos\alpha + \frac{\tan\varphi \cdot \sin\alpha}{F_s}$$

In a manner similar to the Fellenius method, the yield seismic intensity based on the Bishop method is obtained as

$$k_y^* = \frac{R\Sigma\left[\left\{c \cdot b + (W - u \cdot b)\tan\varphi\right\}/m_\alpha\right] - \Sigma W \cdot x_g}{\Sigma W \cdot y_g} \quad (15)$$

2.2 Modified Newmark Approach

As mentioned earlier, the changing position of the sliding mass over the time intervals in the seismic data is ignored in the conventional Newmark sliding block approach. Thus, the values for x_g and y_g in Eqs (10) and (15) do not change along with the other parameters for the slip surface and sliding mass, resulting in yield seismic intensity that does not change over time. In fact, when the earthquake acceleration is large enough (i.e., greater than yield seismic intensity k_y), the sliding mass moves downwards and the values for x_g and y_g change accordingly. Therefore, k_y follows Eqs. (10) and (15) as a function of time. Subjected to horizontal acceleration, the sliding mass moves more horizontally than downwards, so x_g usually decreases a lot and y_g increases a little. As a result, yield seismic intensity k_y in Eqs. (10) and (15) will increase during earthquake shaking.

In addition, when applying the method of slices (Fellenius or Bishop method) in the conventional Newmark approach, the sliding mass above the slip surface is only subdivided once into vertical slices at the initial static state, as shown in Fig. 2a. However, when the sliding mass moves, the edges of the slice are no longer vertical (the solid line) as they were at first (the dotted line), as shown in Fig. 2b, so the assumption of the method of slices does not hold. To overcome this, the sliding mass is re-divided into new slices at each interval of the seismic data when the calculated sliding displacement has a non-zero value at that time interval, i.e., the sliding mass moves in a downslope direction, as illustrated in Fig. 2c. After that, each term in Eq. (1) is recalculated to obtain the final displacement.

A modified Newmark procedure is developed to address the above-mentioned drawbacks. The determination of the yield seismic intensity is carried out in this modified version based on the Fellenius and Bishop methods. The effect of the changing position of the sliding mass during an earthquake on the predicted permanent displacements is also considered. The step-by-step numerical procedure for the modified Newmark sliding displacement approach is outlined as follows:

(1) Determine the critical slip surfaces and associated minimum factors of safety of a slope during an earthquake by Eqs. (9) and (14).
(2) For a chosen slip surface, obtain the yield seismic intensity by Eqs. (10) and (15).
(3) Calculate each term in Eq. (1) at each time step of the seismic data.
(4) Evaluate the magnitude of the sliding displacement using Eqs. (7), (11), (12), and (13).
(5) If the sliding displacement value is not zero, proceed to re-divide the sliding mass into new slices at that time step.
(6) Repeat steps (3) to (5) until the end of the seismic data and finally obtain the accumulation of sliding displacements.

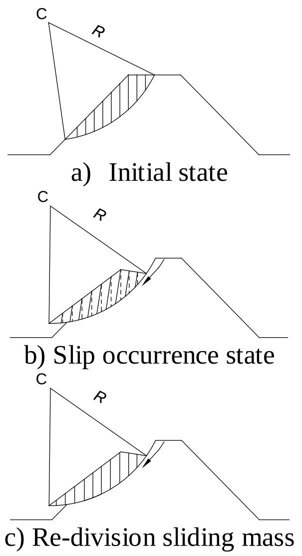


Fig. 2 Modified Newmark approach

3. VERIFICATION

3.1 Target Agricultural Dam

To verify the applicability of the modified Newmark procedure, an agricultural earth-fill dam, the Ijira Dam, 18 m in height and located in Yamagata City, Gifu Prefecture, Japan, was analyzed. This dam was under repair from 2016 to 2017, but this study only focuses on analyzing it before its repair. As a means of verification, the results obtained by the proposed approach were compared with those obtained from the conventional Newmark approach.

Figure 3 shows the maximum cross section of that dam. The dam is mainly composed of a core (material No. 2), inner shells (material No. 3), and outer shells (material Nos. 4 to 7). The soil parameters of the foundation and fill materials in the dam, reported by Nishimura et al. [7] and shown in Table 1, were adopted in this study. Material No. 7 has three values corresponding to the three calculated cases in this study. Specifically, Case 1 for material No. 7(a) is the parameter for material No. 7 obtained from the experimental results, while Cases 2 and 3 correspond to material Nos. 7(b) and 7(c), which are the assumed parameters of material No. 7, whose shear strength parameters were intentionally reduced in order to examine the effectiveness of the proposed approach on the sliding displacement.

Table 1 Soil properties of Ijira Dam

No. soil	Saturated weight (kN/m^3)	Unsaturated weight (kN/m^3)	Friction angle (^{o})	Cohesion (kN/m^2)
1	21.00	18.90	38.50	8.00
2	19.80	18.80	26.00	4.80
3	23.10	22.70	43.30	24.70
4	22.70	22.50	33.10	147.30
5	23.00	22.70	33.50	90.10
6	22.40	22.20	36.80	11.70
7(a)	21.00	19.10	28.70	6.50
7(b)	21.00	19.10	24.00	5.00
7(c)	21.00	19.10	22.00	4.00

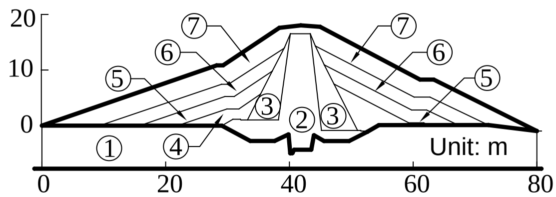


Fig. 3 Cross section of Ijira Dam

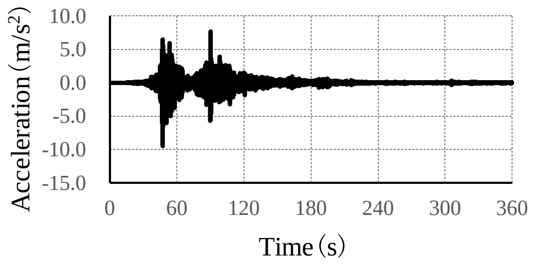


Fig. 4 Acceleration waveform of input motion

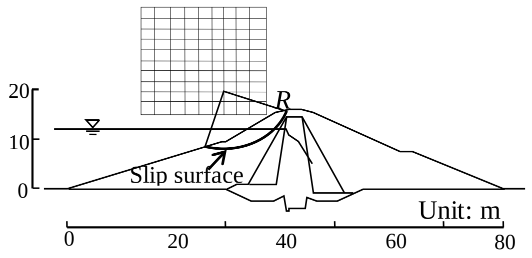


Fig. 5 Circular slip surface in the analysis

The input acceleration time history in the horizontal direction, used in this study and based on the EW component of the 2011 off the Pacific coast of Tohoku-Pacific Earthquake, is shown in Fig. 4. The data from Ofunato Station were obtained from the Japan Meteorological Agency website [14]. In addition, the water level upstream of the dam is considered in this study. According to [15], the normal water level (NWL) is used to evaluate the seismic performance of the dam against level 2 earthquake motion. For the Ijira Dam, the water level is 3.45 m lower than the crest of the dam.

To facilitate a comparison of the results between methods, a slip surface (radius R = 11 m) is used in this study, as shown in Fig. 5. This slip surface is a slip surface showing 0.156, which is the minimum yield seismic intensity obtained by the seismic intensity method by changing the radius every 0.5 m around each grid point in Fig. 5. Also in this figure is the phreatic line through the dam, obtained from the steady seepage analysis, which is not presented in this paper.

3.2 Results And Discussion

Figure 6 presents the results of the sliding displacement based on the Fellenius and Bishop methods for the three calculation cases when the conventional Newmark approach is applied. It can be seen that, in Case 1, the sliding displacement is small with both Fellenius and Bishop methods. The difference between the two methods is not significant, with the results of the Fellenius method being slightly larger than those of the Bishop method by about 0.16 m. However, in Cases 2 and 3, since the shear strength parameters of soil material No. 7 are assumed to have decreased, the sliding displacements with both methods are larger than in Case 1, especially that of Case 3. The application of the Bishop method yielded smaller results than the Fellenius method, as was analyzed in section 2. Moreover, it was found that, with the conventional Newmark approach, the difference between the Fellenius and Bishop methods is large when the sliding mass moved as much as it did in Case 3 (Fig. 6c).

The results of the sliding displacement with the Bishop and Fellenius methods for the three cases are shown in Fig. 7 according to the modified Newmark approach. It can be clearly seen that the results of the Bishop and Fellenius methods have decreased, especially those with the Fellenius method in Case 3. The difference between the Fellenius and Bishop methods is no longer as large as with the conventional Newmark approach. This proves that the re-division of the sliding mass in the modified Newmark approach is effective with both Bishop and Fellenius methods.

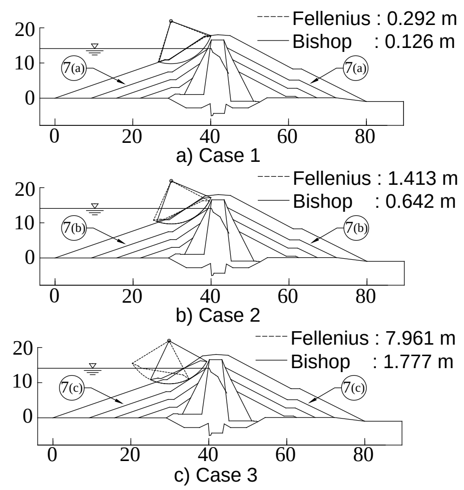


Fig. 6 Sliding displacement results with Conventional Newmark approach

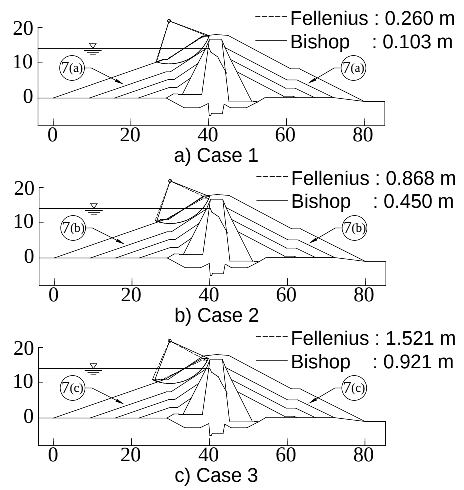


Fig.7 Sliding displacement results with Modified Newmark approach

To clearly see the effect of the changing position of the sliding mass over the time steps, the change in the sliding displacement of the sliding mass with each time step should be considered. Although the sliding displacement results for the three cases tend to be similar during an earthquake, only the results for Case 2 are analyzed, as shown in Fig. 8. The results of the Fellenius (dashed line) and Bishop (solid line) methods, calculated according to the modified Newmark approach, are shown in Fig. 8, while those of the calculation according to the conventional Newmark approach are shown as dashed (Fellenius method) and solid (Bishop method) lines with circular symbols. It is found that the results of both Fellenius and Bishop methods for the two approaches tend to be the same. The sliding mass began to move after the 40^{th} second when the earthquake acceleration was greater than yield seismic intensity k_y at the first strike of seismic motion (Fig. 5). Then, the sliding mass continued to slide until the 60^{th} second, at which point the earthquake acceleration started to be less than k_y. The sliding mass stopped moving until the 80^{th} second. At the 80^{th} second, the second strike of seismic motion occurred with an acceleration greater than k_y, and the sliding mass moved again until the 110^{th} second. The sliding mass was completely still for the remainder of the seismic motion with earthquake accelerations less than k_y. However, in the modified Newmark approach, due to the change in the sliding mass position at each time step, the sliding displacement value in this approach with both Fellenius and Bishop methods was smaller than that in the conventional Newmark method, as shown in Fig. 8.

It can be seen that the movement of the sliding mass depends on the seismic acceleration as well as yield seismic intensity, k_y. The conventional Newmark approach now often takes k_y as a constant value in seismic slope stability analyses [4,15-17]. This leads to very conservative results since the actual yield seismic intensity changes over time during shaking. As analyzed in section 2, when taking into account the change in the sliding mass position, k_y will increase during an earthquake. This is clearly shown in Fig. 9 for Case 2, and the other cases are similar. In the conventional Newmark approach, k_y remained constant with both Fellenius and Bishop methods, while in the modified Newmark approach, k_y increased with these two methods, corresponding to two strikes of seismic motion. The trend in the change in k_y is similar to that of the displacement results for the above-analyzed sliding mass.

Thus, it can be seen that the modified Newmark approach yields sliding displacement results for the sliding mass that are smaller than those of the conventional Newmark approach. In other words, that approach provides less conservative results. As mentioned previously, the permanent displacement of the sliding mass is an important parameter for verifying the seismic performance of an earth dam against earthquakes, that is, through a comparison of the calculated sliding displacement value and the allowable settlement of the dam.

According to the design guidelines for land reclamation projects, "reservoir maintenance" [18], it is difficult to give specific values for the allowable settlement of reservoirs, but they include (1) the difference in elevation between the top of the dam and the normal water level (NWL), (2) the difference in elevation between the top of the dam and the designed high water level (HWL), and (3) 1.0 m (taking into account the extra height and freeboard). It can be seen that with hypothetical Cases 2 and 3, when calculating according to the conventional Newmark approach, it is highly possible that the results of the sliding displacement will be larger than the allowable settlement, especially with the Fellenius method. Accordingly, no guarantee can be given for the dam’s seismic performance against level 2 earthquake motion. This will lead to a costly, wasteful solution for ensuring the dam's performance against level 2 earthquake motion.

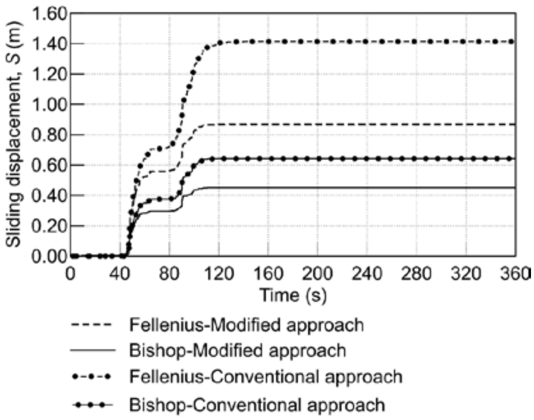


Fig. 8 Sliding displacement with time for Case 2

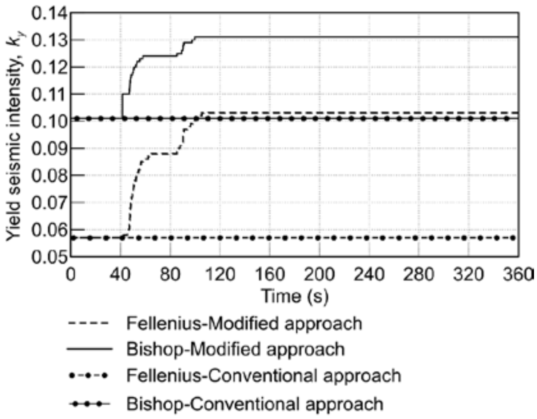


Fig. 9 Yield seismic intensity with time for Case 2

However, when applying the modified Newmark approach, the results of the sliding displacement are smaller than the allowable settlement with both Fellenius and Bishop methods for Case 2, and with the Bishop method for Case 3. Therefore, the application of the modified Newmark approach, combined with the Bishop method, will provide a less conservative design solution.

4. CONCLUSIONS

In this study, a modified Newmark approach has been presented to evaluate the earthquake-induced permanent displacement of an earth dam based on the changing position of the sliding mass by re-dividing the sliding mass by time steps when slip occurs. Comparing the results of the modified and the conventional Newmark approaches, there is a noticeable difference between the obtained displacements. The difference confirms that ignoring the change in the slip surface position during an earthquake can produce an inconsistent yield seismic intensity (constant value), and result in an overly conservative displacement estimate. Through verification for one agricultural dam, with two hypothetical cases (cases 2 and 3), the displacement results, according to the conventional Newmark approach, may be outside the allowable settlement range with both methods Fellenius and Bishop. But with the modified Newmark approach, the values of that displacement are still within that range with both methods Fellenius and Bishop for case 2 and with the Bishop method for case 3. Thus the modified Newmark approach, combined with the simplified Bishop method, a method that is stricter than the Fellenius method, leads to a more realistic assessment of the permanent displacement in seismic slope stability analyses.

5. ACKNOWLEDGMENTS

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