Assessment of Newmark Methods for the Prediction of Deviatoric Displacement of Earth Dams Using Energy Approach

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Abstract

n this research, permanent earthquake-induced deformations of earth dams using Newmark methods are investigated. For this purpose, the errors of all sliding block methods for the prediction of the permanent deformation of 25 real earth dams are discussed in the time domain. Also, the importance level of some related parameters, discussed by previous studies, is scrutinized using energy approach. The results of the study revealed that, the energy value, related to the velocity time history, not only acts as a separator parameter between conservative and non-conservative predictions of sliding block methods but also has a significant impact on the prediction of permanent earthquake-induced deformations of earth dams.

Keywords: Energy Approach, Earth Dams, Newmark Methods.

1. INTRODUCTION

Since Newmark's 1965 rankine lecture[1], prediction of the earthquake-induced permanent deformation of earthen structures using sliding block method has been discussed by many researchers. Many investigators, taking different approaches, further modified Newmark model. All the methods proposed by different researchers can be categorized in two classes of "the methods which do not consider the sliding block response (Rigid approach)" and "the methods which consider the sliding block response (Decoupled and Coupled approaches)". Advantages and disadvantages of each approach have been discussed by previous studies in detail.

Bray and Rathje [2] indicated that the results of the original method led to non-conservative predictions when the fundamental period of the system is close to the mean period of the acceleration time history. On the other hand, this approach resulted in conservative predictions for large values of period ratio (for example Ts/Tm =4). In addition, when yield acceleration is greater than PGA, the estimated deformation using rigid approach inherently is equal to the zero. Although decoupled approach eliminated some deficiency of rigid approach, it has its own disadvantages. The results of the study by Kramer and Smith [3] revealed that the decoupled approach estimated very conservative results when Ts/Tm ratio was less than one. Lin and Whitman [4] studied the decoupled approximation using a lumped mass shear beam model with linear elastic material properties. They analyzed shallow, deep, and intermediate sliding systems. They indicated that at ky/kmax value of 0.5 and material damping ratio of 15%, the decoupled approximation overestimated the exact displacement, (exact displacement obtained from coupled approach) by an average of 20%. However, this finding did not indicate that the decoupled approach was always conservative. Moreover, they did not investigate when ky/kmax exceeded 0.5, how would be the calculated displacement. However, Rathje and Bray 1999 [5] concluded that the above conservatism decoupled approximation was right only for small ratio of ky/kmax (for example Ky/Kmax=0.6) and Ts/Tm of less than 2. Furthermore, for large values of ky/kmax or Ts, prediction of decoupled approximation may be non-conservative. Nevertheless, for large values of both ratios, it is expected that the calculated permanent deformations, using both coupled and decoupled approaches, are naturally small. Bray and Rathje [6] also indicated that nonlinearity of slippage behavior is more important than nonlinearity of material behavior in the cases of Ts/Tm less than one. On the other hand, for large values of Ts/Tm,the nonlinearity of material behavior can have significant impact on the permanent displacement prediction using coupled approach. Such nonlinearity also can cause an increase in the fundamental period of the system due to decrease in theshear modulus of material. Hence, Bray and Travasarou [7] used 1.5Ts instead of Ts for the development of a new nonlinear coupled method by running 55000 analysis and using 688 records related to 41 earthquakes. Then,they calibrated their model using 16 case studies. Their method eliminated almost all the deficiencies of previous methods.

More recently, Garini et al.[8] studied rigid sliding block system under near-field motions by discussing the sequence of high-duration pulses importance. Afterward, Voyagaki et al. [9] by applying near-field normalized pulses on sliding block system concluded that for constant values of PGA and material shear strength, existence of half-cycle pulse may result in larger permanent deformation compared to full-cycle pulse. This conclusion contradicted the common understanding, such as e.g. Yegian et al. [10]. Later, Gazettas et al. [11], applied number of records containing forward directivity and fling step effects on sliding system and discussed slip nature and its relation with PGV, dominant period of the velocity pulse and polarity of velocity pulse. They also indicated that vertical component of the applied strong motion had no significant effect on the sliding systems. It is worth noting that, researchers such as Franklin and Chang [12]; Yegian et al. [13]; and Kramer and Lind wall [14], have previously mentioned some of these finding. Following previous studies, Garini and Gazettas [15] indicated that the damage potential of the near-field strong motions may be much greater than what was previously considered. So, they defined an upper bound for deformation of rigid sliding systems under near-field ground motions. However, the accuracy of this method was not examined using real case studies.

However, some other studies such as Meehan and Vahedifard [16], which discussed performance of the methods using case studies, indicated that some developed methods (which did not include Garini and Gazettas method[12]) may underestimate results despite their complexity in calculation and analysis, especially for large values of occurred deformations.However,none of these type of studies introduced a clear separator parameter for the definition of a boundary between conservative and non-conservative predictions in time or frequency domains.

In the present study, the calculated deformation obtained by Newmark methods, for ten real cases are discussed in detail. In order to achieve this goal, all the Newmark methods were classified in two groups: 1-Methods which do not consider response of sliding system (the methods which are derived from rigid approach)& 2-Methods which consider response of sliding system (the methods which are derived from decoupled and coupled approaches). Then, a total of 10 earth dams, which experienced known amount of displacements during a known earthquake, were selected. The strong motions used for analyzing the earth dams were the same recorded motion at the dam site. All the required parameters including yield acceleration, PGA, PGV, Arias Intensity, Initial fundamental period (Ts), earthquake Magnitude, Distance between site and energy source, Sa(1.5Ts) and etc. for calculation of the permanent deformation of the earthen structures using all the simplified and rigorous Newmark methods were obtained directly for each case. The permanent deformation of these case studies were estimated by 32 values of 26 methods. The predicted values were compared with deviatoric deformation of the recorded cases to determine conservative and non-conservative method. So, the error between predicted and observed deformations for each method has been discussed in time domain for this group of case studies and consequently, an effective parameter has been introduced. Finally, for the sake of checking the results of Group 1, a total of 15 earth dams, included in Group 2 of earth dams, have been analyzed using sliding block methods. The necessary parameters for analyzing Group 2 of case studies, mainly have been obtained from previous studies and attenuation relationships. The results of Group 2 have confirmed the conclusions made for the analysis of Group 1.

2. DISCUSSION OF FUNDAMENTAL CONCEPTS

2.1. NEWMARK FAMILY METHODS

All the Newmark methods are categorized and introduced in tables 1, 2. As indicated, 32predicted values resulted from 26(rigorous and simplified) methods within two categories are discussed in this research.

Table 1. List of the methods which do not consider response of sliding block system

1.Rigorous Method (Newmark 1965)	2.Newmark Simplified (mean): by Newmark	3.Newmark Simplified (mean): by Cai 1996
4.Franklin & Chang- (Whitman & Liao 1977)	5.Ambraseys & Menu (Median) 1988	6.Jibson et al (1993)
7.Jibson et al 1998 & 2000	8.Jibson et al (2007) (a)	9.Jibson et al (2007) (b)
10.Jibson et al (2007) (c)	11.Jibson et al (2007) (d)	12.Watson-Lamprey and Abrahamson(2006)
13.Saygili & Rathje (2008) (a)	14.Saygili & Rathje (2008) (b)	15.Saygili & Rathje (2008) (c)
16.Saygili & Rathje (UpperBound.)2009	17.Ebling (Mean) 2009	18.Rathje and Antonakos (PGA,M) a
19. Rathje and Antonakos (PGA,PGV)a	20. Garini and Gazettas 2012–Upper Boundb	
Methods 18 & 19 are unified methods. Initial valuesof these methods areestimated by method 16 and final valuesareobtained using decoupled approach. Method 20 is developed by applying Near-Field strong motions on rigid sliding system.		

Table 2. List of the methods which consider response of sliding block system

21, 23.Seed and Makdisi 1978 (Upper Bound & Lower Bound)	22.Seed and Makdisi 1978 (Mean: by Gazettas & Dakoulas 1992)
24.Hynes-Griffin & Franklin1984 (mean)	25.Bray 1998
26.Rigorous Linear Elastic Decoupled (Bray & Rathje 1999a)	27.Rigorous Equivalent Linear Decoupled (Bray & Rathje 1999a)
28.Rigorous Linear Elastic Coupled (Bray & Rathje 1999a)	29.Rigorous Equivalent Linear Coupled (Bray & Rathje 1999a)
30, 31, 32.Bray and Travasarou 2007 (Upper Bound, Mean and Lower Bound)	

2.2. YIELD COEFFICIENT(KY)

The pseudo-static analysis was applied in this study, for all methods, to obtain yield coefficient. The Morgenstern-Price's Method was used as a limit equilibrium method in pseudo-static analysis. All the properties of the dams are obtained from their real conditions during the earthquake and analysis were performed in total stress or undrained condition as recommended by Newmark [1]. Finally, due to the effects of cyclic loading, the yield acceleration, calculated by the pseudo-static analysis, has been reduced by 10 percent[17]. Therefore, all the yield accelerations used in this study were the theoretical yield accelerations that were obtained from the mentioned procedure and other type of procedures such as back-analysis and lab-tests were not considered in the present study.

2.3. OBSERVED DEVIATORIC DEFORMATION

Observed deviatoric deformations, including both deformations related to the sliding block movement on the inclined slip surface and also related to the volumetric contraction of sliding block, have been calculated in the present study for all cases by distributing the values of the observed max horizontal and max vertical deformations on the related inclined slip surface and then accumulating of distributed deformation. It is worth noting that the obtained deviatoric deformation by this procedure is mainly related to horizontal component of the observed deformations [18].

2.4. INITIAL FUNDAMENTAL PERIOD (TS)

The expression of Ts=2.6H/Vs has been used in order to estimate initial fundamental period of sliding block wedge. Note that H is the sliding block depth which the geometry of sliding block has been obtained by pseudo-static analysis, as mentioned in section 2.2. Therefore, the height of sliding mass when sliding is triggered is considered as H. In addition, Vs is the average shear wave velocity of the sliding mass.

3. DISCUSSION OF RESULTS:

The results of this study are presented in two parts of 3.1 and 3.2 for Group 1 and 2, respectively.

3.1. ANALYZING GROUP 1 OF CASE STUDIES (10 EARTH DAMS)

3.1.1. GROUP 1 OF CASE STUDIES

The Group 1 of case studies (table 3) includes 10 dams, all located up to 15 kilometers from the related fault, and were shaken with an earthquake of Mw>5.8. In addition, none of these cases have experienced liquefaction or failure phenomenon during the related earthquake. In other words, all the displacements for the ten cases were related to the movement of sliding block wedge during related earthquake. Also, all the properties of these 10 dams such as recorded strong motion, material properties, geometry and etc. were precisely available. In other words, their deformations can be predicted using all the 26 methods (all the rigorous and simplified methods of tables 1 and 2) using precise parameters. For this group of case studies, all the required parameters such as yield acceleration, ground motion parameters and etc. were calculated in this study. The details of earth dams included in Group 1, are presented in table3.

Table 3. The detail of Group1 of case studies

Case No.	Case Name	Height (m)	Earthquake	Mw	Closest Distance to Fault(km)	Displacement (mm)	
						Horizontal	Vertical
1	Anderson Dam	72	Morgan Hill 1984	6.1	3.3	9	15
2	Cogswell Dam	81	Sierra Madre 1991	5.8	4	41	16
3	Coyote Lake Dam	43	Morgan Hill 1984	6.1	1.5	37	67
4	La Villita Dam	60	Mexico 1975 (15 Nov)	5.9	10	16	24
5	Lexington Dam	63	Loma Prieta 1989	7.0	5	76	259
6	Long Valley Dam	38	Mammoth Lake 1980 (main shock)	6.1	15	Minor 1	
7	Los Angles Dam	40	Northridge 1994	6.7	6	55	90
8	Matahina Dam	86	EDGECUMBE 1987	6.5	12	268 Dst	102
9	Oroville Dam	235	Oroville 1975	6.0	8	15	10
10	Whittier Narrows Dam	29	Whittier Narrows 1987	6.1	7	Minor	
Minor Means <5mm							

As mentioned above, strong motions used for analyzing Group 1 earth dams, were the same motions recorded at the dam sites during the related earthquake. It is worth noting that the applied record for each earth dam, for using in the Newmark family method analysis, was calculated at the base of sliding block using numerical analysis when the height of sliding wedge was less than the height of dam.

Note that the recorded strong motion in the south-west abutment of coyote lake dam during Morgan Hill 1984 earthquake, in the transverse direction had a PGA equal to 0.65g. However, the base acceleration for the coyote lake dam has been scaled down to PGA=0.36g, as recommended by Boore et al [19]for this dam site. In addition, the strong motion used for analyzing Whittier Narrows dam was the strong motion recorded at the crest of dam. However, this record was scaled to a target response spectrum which was obtained from attenuation relationship developed by Ambraseys & Douglas [20] for Near-Field Regions. The details of mentioned recorded strong motions in the transverse component are presented in table 4.

Table 4. Strong motions recorded at the dam site, used as the horizontal transverse base record

Case No. due to Table 6	Station in the dam site	Comp.	Operations on Record	SED (cm2/s)	SMV (cm/s)	PGV (cm/s)
1	Down-Stream toe	250	--	322	15.21	27.6
2	Right Abutment	60	--	34	3.71	9.55
3	South-West Abutment	195	Scaled to the target response spectrum which obtained from attenuation relationship recommended by Ambraseys & Douglas 2003 for Near-Field Regions (D<15KM)	342	15.77	26.8
4	Berm (Near the Toe)	S05E	--	24	4.391	5.11
5	Left Abutment	0	--	3102 (3116) a	35.25 (36.00)	84.7 (86.03)
6	Down-Stream toe	90	--	135	6.38	17.8
7	Foundation (on free field)	334	--	3210	31.54	62.2
8	Down-Stream Toe	353	--	1290 (12266)	17.43 (49.24)	20.6 (71.54)
9	Seismological Station	N37E	--	1.4 (15)	1.23 (2.71)	2.25 (4.03)
10	Crest	303	Scaled by the same way which was applied for case number 3	48	6.02	11.3
Values in brackets are related to the records at the base of sliding blocks (for cases: block height≠dam height)						

PREDICTION OF THE DEFORMATIONS FOR GROUP 1

The details of sliding block calculated for each case of Group 1 are presented in table 5. The performance of each method regarding the prediction of the observed max deviatoric deformations of the earth dams, presented in table 3,has been discussed in the following.

Table 5. Details for sliding wedge of case studies obtained from limit-equilibrium analysis

Case No. due to Table6	Static Factor of Safetya	Yield Coefficient (Ky)			Sliding Wedgec	
		Calculated by this studyb	Calculated by other studies		height (m)	Description
			Ky	Reference		
1	1.197	0.059	0.03 for Upstream	USCOLD: J.Ryan et al.2013	72	Deep
2	1.465	0.150	0.15	Singh & Roy 2009	81	Shallow
3	2.346	0.288	--	--	45	Deep
4	1.808	0.198	0.2	-Singh & Roy 2009 -Bray & Travasarou 2007	65	Deep
5	1.814	0.230	0.23	Santa Clara Valley Water District 2004 Report No. LN-4	25	Deep
6	2.046	0.243	0.23	Singh & Roy 2009	36.3	Shallow
7	2.269	0.198	0.15	Singh & Roy 2009	45	Deep
8	1.641	0.153	0.17	Singh & Roy 2009	15	Shallow
9	1.692	0.198	0.21	Singh & Roy 2009	106	Shallow
10	2.386	0.315	--	--	16.3	Deep

Using Morgenstern-Price's Method
Using Pseudo-Static a
Details of all analysis have been explained in the thesis published in IUST:
“Evaluation of sliding block methods performance for the estimation of permanent deformation of earth dams located in Near-field regions” By Reza Karimi Moghaddam 2017

In order to analyze each earth dam, the strong motion,recorded in the dam site, has been used as mentioned above. Then, the permanent deformation for each case has been calculated using the recordedstrong motion using all the simplified and rigorous Newmark methods (32 values of 26 methods). Finally, the errors between observed and predicted permanent deformations,using allthe methods, have been discussed.

The performance of the methods are indicated in figures 1 and 2. Figure 1 is related to the methods which do not consider the response of sliding systems (Rigid-based methods), while figure 2 is related to the methods which consider response of sliding block system (Decoupled-based and Coupled-based methods). The vertical axis of these figures are calculated deformations by the methods and the horizontal axis are observed deviatoric deformation for each earth dam. Also, the 45 degree lineshave been drawn to separate conservative and non-conservative predictions. Hence, it is clear that the points, located at the top of 45’ lines, are related to the conservative predictions and on the contrary, the points located at the bottom of 45’ lines are related to the non-conservative predictions.

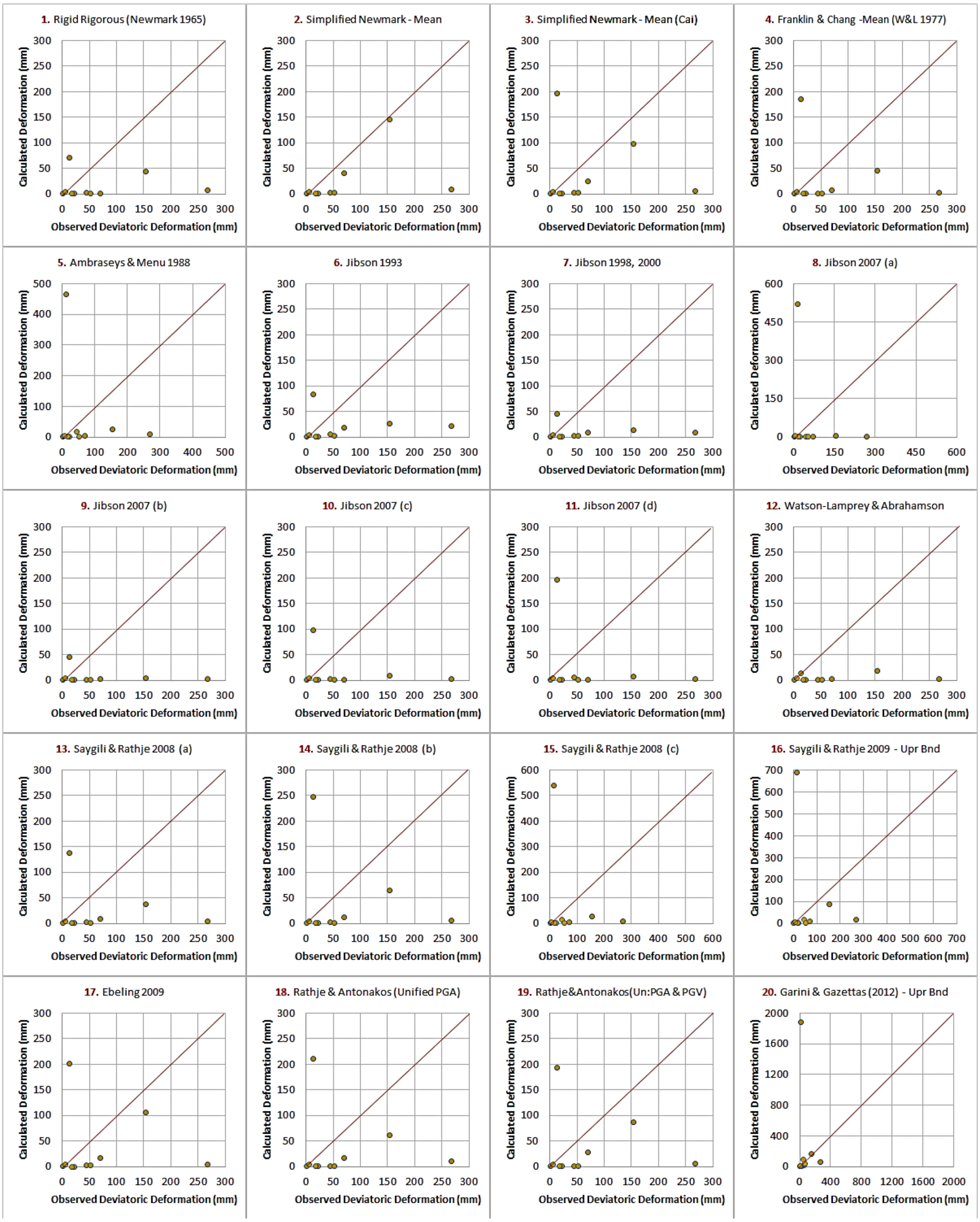

Figure 1. Calculated displacement bydifferent rigid-based, Unified and Near-Field methods versus observed max Deviatoric deformation of 10 case studies (Group 1)

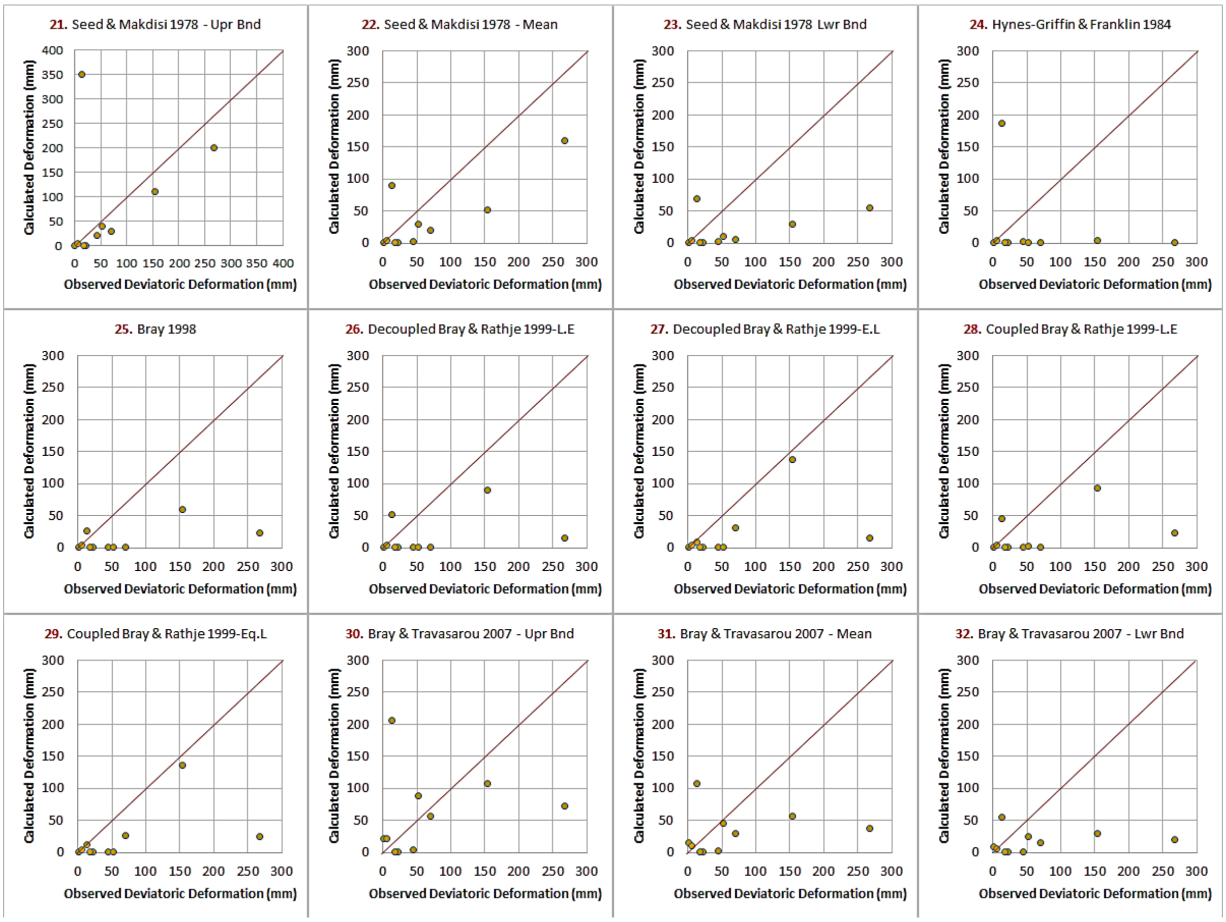

Figure 2. Calculated displacement bydifferent decoupled-based and coupled- based methods versus observed max Deviatoric deformation of 10casestudies (Group 1)

DESIGNEE METHOD

As seen in figures 1 and 2, the method developed by Bray and Travasarou 2007 [7] estimates the best results and so, this method is known as the designee method in this study. This method has the highest number of acceptable (conservative) predictions and lowest rate of negative errors (the lowest error when is underestimated) among all the methods for the prediction of permanent deformation of theearth dams. Note that also, the method developed by Garini and Gazettas 2012 [15] has equal number of conservative predictions compared with this method. However, the absolute amount of negative errorsfor Garini and Gazettas [15] method are higher than Bray and Travasarou [7] method. This means that when two methods result in underestimated predictions, the Garini and Gazettas [15] method is more non-conservative than the Bray and Travasarou [7] method. Also, the upper bound of Seed and Makdisi 1978 method and the upper bound of Saygili and Rathje [22] method have the best results among decoupled and rigid methods, respectively.

DISCUSSION OF THE RESULTS FROM THE ENERGY POINT OF VIEW

It is well known that the near-field strong motions are different in content compared with far-field motions. The energy generated by an earthquake is depreciated by the earthquake wave travelling from near-field to far-field. The orientation of site toward the wave emission direction has also its own impact on the accumulation of energy in the near-field regions as well as rupture velocity. It is well accepted that the earthquake energy can present the effect of an earthquake in a site better than other parameters such as PGA or PGV. In fact, the accumulation of energy in a site is a generic parameter for defining effect of an earthquake in any site.

To express energy concept in time domain in this study, the cumulative squared velocity of recorded strong motion in the dam site is used. This parameter is also known as recorded specific energy density which is derived from the site specific energy density [23].

Site Specific Energy Density $=\frac{\beta s.\rho s}{4}\int v^2(t)dt$ (1)

Recorded S.E.D = Cumulative Squared Velocity $=\int V^2(t)d(t)$ (2)

The values of specific energy density, computed for all the earth dams of table 3, are indicated in table 4.
The absolute errors of Bray and Travasarou [7] method (Designee method in this study)versus SED are depicted in figure 3 using the below expression:

Absolute Error (%) =D $_{\text{Calculated}}$ – D $_{\text{Observed}}$ (3)

Note that, vertical axis of figure 3isabsolute error which is calculated by equation (3). It is obvious that in this figure, the positive errors are related to the conservative and the negative errors are related to the non-conservative predictions. Also, horizontal axis of this figure is SED which is calculated for each earth dam using equation (2). The velocity time history used in equation (2) is obtained from the recorded strong motion acceleration at the base of related sliding block.

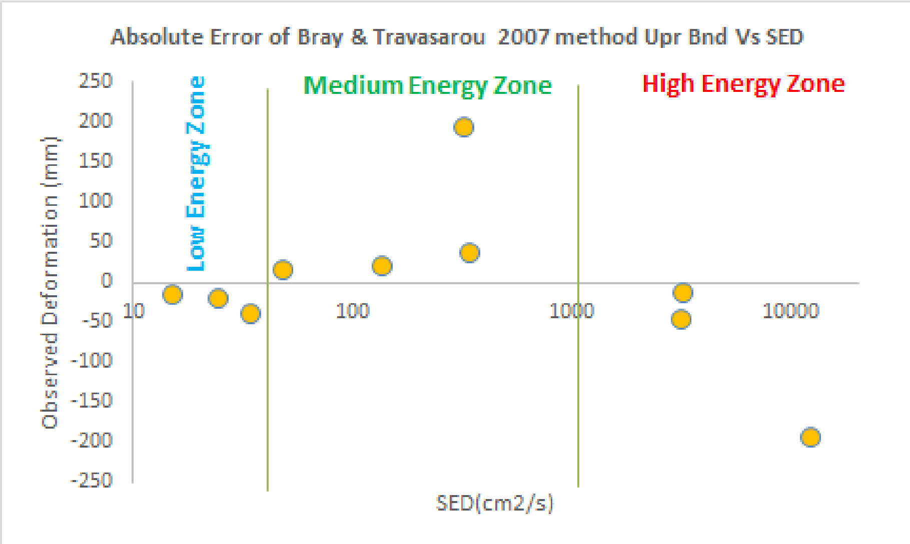

Figure 3. The absoluteerrors of the upper bound values of Bray and Travasarou 2007 coupled-based method (the designee method), for estimating max deviatoric deformations versus SED of the Group 1 case studies

As illustrated in figure 3, the predictions of designee method are non-conservative for high values of SED (i.e. SED > 1000 cm^2/s) and for small values of SED (i.e. SED <50 cm^2/s). On the other hand, this method predictions are generally conservative in the medium values of SED. Although figure 3 only proves the mentioned conclusion about Bray and Travasarou [7] method, but this conclusion is also valid about all the methods of tables 1 and 2.In addition, although the figure 3 only depicts the errors of max deviatoric deformation predictions, but this conclusion is also valid about max horizontal and max overall deformations. (Max overall deformation is defined as the maximum of max horizontal and max vertical deformations).

Since SED is directly calculated from a velocity time history, it is expected to have a rational relationship with PGV for an earthquake. However, since SED is obtained from the square root of the velocity time series, it is logic to say that PGV does not present the full content of SED. In addition, since SED concept considers the amount of PGV in positive and negative positions, it seems that the parameters, such as sustained maximum velocity (SMV)which are associated with velocity time history and related cycles, to act partly the same way which SED does. Note that, SMV gives the sustained maximum velocity during three cycles, and is defined as the third highest absolute value of velocity in the time-history (note: in order for an absolute value to be considered as a "maximum", it must be larger than values 20 steps before and 20 steps after). The SMV values, computed for all earth dams of table 3, are indicated in table 4. In figure 4, absolute error of Bray & Travasarou [22] method (designee method in this study) for all 10 earth dams is also depicted against SMV. As it is depicted in this figure, the Designee method results in conservative predictions only in medium values of SMV which shows the same trend as is established for SED.

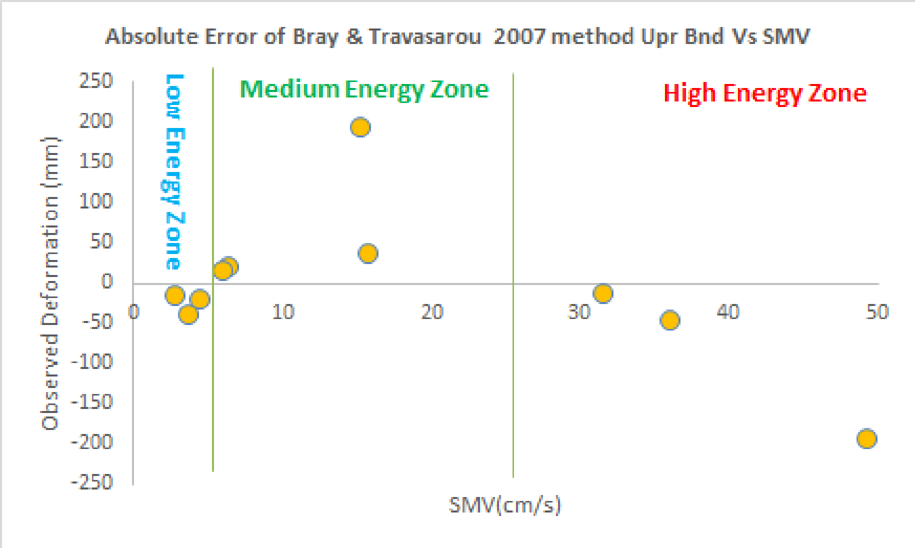

Figure 4. The absoluteerrors of the upper bound values of Bray and Travasarou 2007 coupled-based method (the designee method), for estimating max deviatoric deformations versus SMV of the Group 1 case studies

Although figure 4 only depict Bray and Travasarou [7] method, but this conclusion is also valid for all the methods of tables 1 and 2 and also about max horizontal and max overall deformations.

Furthermore, although SED and other parameters such as SMV which are related to the experienced energy in a site, act as a separator parameter between conservative and non-conservative results in time domain, it seems that they have a direct impact on occurring permanent deformation of earthen structures during an earthquake as well as other parameters such as Ky. Figure 5 indicates observed deviatoric deformations (Vertical axis) against associated SED (Horizontal axis). Despite the fact that other parameters such as Ky and Ts affect deformation of earth dams, figure 5indicates that observed deviatoric deformations increase with increasing SED of transverse component of base motion. For the cases with low and medium values of SED, small values of deviatoric deformations occur (for example <5cm) despite having different values of ky in the range of 0.06-0.32. On the other hand, the large values of permanent deformations occur in the large values of SED. Figure 6 indicates observed deviatoric deformations (Vertical axis) against associated SMV (Horizontal axis). As it is seen in figure 6, all above discussions are valid about SMV too.

Overall, it seems rational that considering energy concepts can eliminate some errors related to calculation of earthquake-induced permanent deformation of earthen structures.

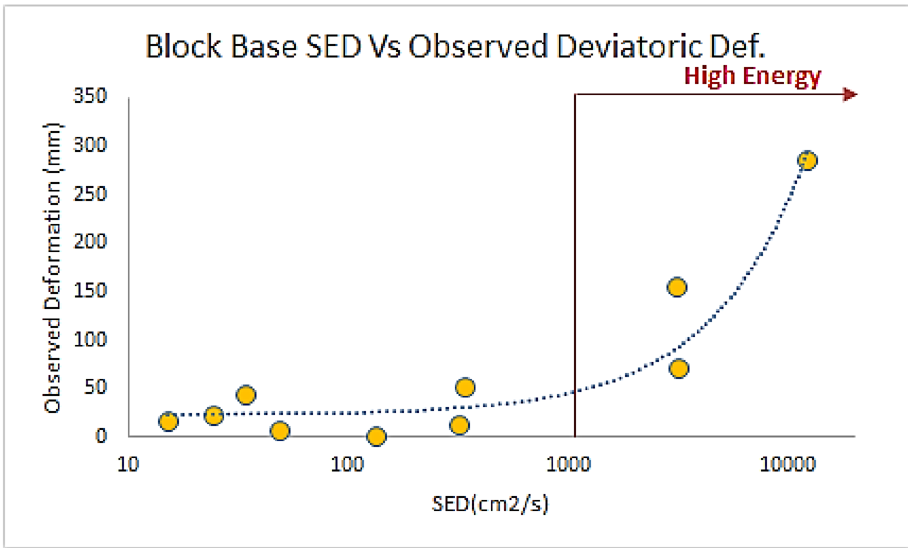

Figure 5. Observed deviatoric deformations versus Specific Energy Density (SED) for Group 1 case studies

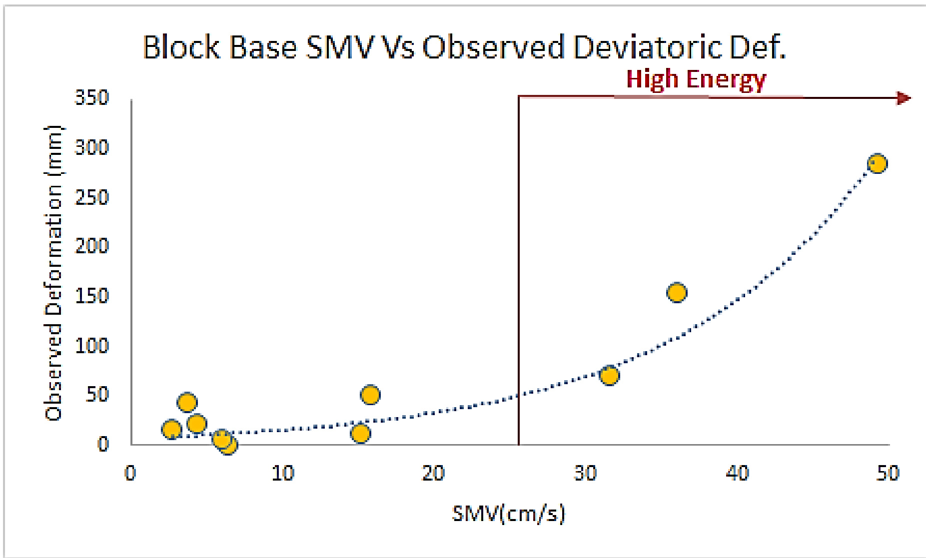

Figure 6. Observed deviatoric deformations versus SMV for Group 1 case studies

ANALYZING GROUP 2 OF CASE STUDIES (15 EARTH DAMS)

The list of 15 earth dams, as Group 2, are presented in table 6. All the necessary parameters for the purpose of analysing Group 2 earth dams, were obtained from previous studies. However, in order to estimate the response of the sliding systems, attenuation relationships were used. However, since PGAs of the strong motions for Group 2 of case studies were available (or suggested by previous studies), the attenuation relationships used in this study were recalibrated using sigma parameter which was obtained from try and error process. For this purpose, first, the sigma parameter of an attenuation relationship was changed enough to achieve the desired PGA. Then, the exact response of the system was calculated using the attenuation relationship and the obtained sigma. The calculated response, in this way, had the least error such that the results of various attenuation relationships were almost identical in value. However, the relationship developed by Campbell, K.W [24] was used for estimating the response of the systems for the distances of less than 40 kilometers. Also, the relationship developed by Crouse [25], was used to estimate the response of the systems for the distances of more than 40 kilometers. Furthermore, the PGV for each earth dam was calculated using previous mentioned procedure related to attenuation relationships.

Table 6. The details of case studies of Group2

Case Name	EQ Date	M	Dist. (KM)	PGA (g)	Estimated PGV (cm/s)	Height (m)	Ky (g)	Max Deformation (mm)	
								Hor.	Ver.
La Villita	3.14.79	7.6	124	0.1	4.9	60	0.2	12	13
Asagawara	10.23.04	6.8	24	0.12	5.2	56.4	0.08	400	700
El Infiernillo (D/s)	3.14.79	7.6	110	0.23	8	148	0.55	34	46
La Villita	10.25.81	7.3	121	0.174	8.5	60	0.2	24	114
Demi	1.26.01	7.6	90	0.2	11.3	17	0.26	100	50
Sasoi	1.26.01	7.6	120	0.2	12.1	20	0.3	90	25
Surgu	5.5.86	6.6	10	0.21	13.1	55	0.15	1	150
Tapar	1.26.01	7.6	43	0.15	18.4	15.5	0.12	500	800
Chabbot	4.18.06	8.3	32	0.57	28.4	43.3	0.12	225	450
Lower SanFernando	1.17.94	6.9	11	0.32	32.3	32.8	0.15	150	150
Shin Yamamoto	10.23.04	6.8	6	0.55	33.7	44.5	0.36	20	20
Kashi	8.23.85	7.4	21	0.25	34.1	16	0.14	300	400
Kashi	9.12.85	6.8	16	0.5	45.2	16	0.14	1000	1500
Austrian	10.17.89	7	11	0.575	58	21.5	0.21	305	789
Suvi	1.26.01	7.6	37	0.42	62	15	0.09	4000	1100

PREDICTION OF THE DEFORMATIONS FOR GROUP 2

Deformation of the Group 2 earth dams were estimated by the best method of each approach (four methods), introduced in section 3.1, and are indicated in figure 7.

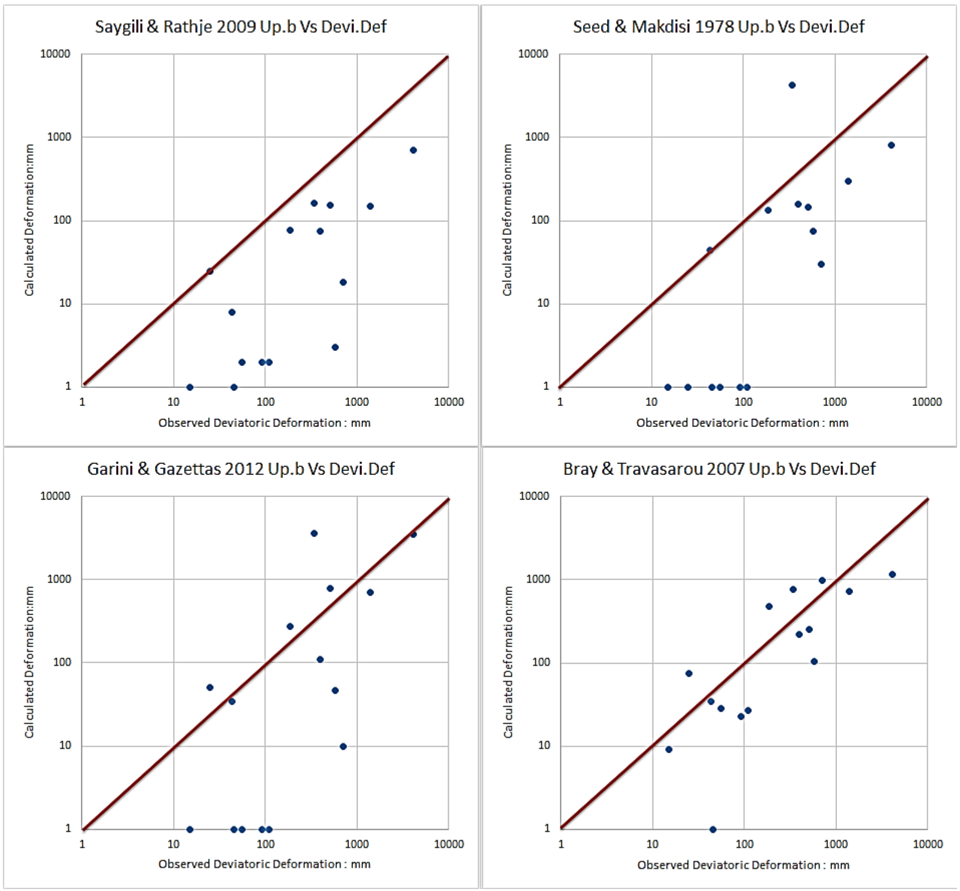

Figure 7. The performance of the sliding blockmethodsfor the prediction of observed max Deviatoric deformation of 15 case studies (Group 2)

As it is clear in figure 7, the method developed by Bray and Travasarou [7] estimates the best results as the same was established for the prediction of Group 1 deformations. This method has the highest number of acceptable (conservative) predictions and the lowest absolute values of negative errors. Note that, the method developed by Garini and Gazettas [15] has also equal number of acceptable predictions compared with Bray and Travasarou [7] method. However, the absolute amount of negative errors for Garini and Gazettas [15] method are higher than Bray and Travasarou [7] method.

4. DISCUSSION OF THE RESULTS FROM THE ENERGY POINT OF VIEW

Since the Energy representative parameters such as SED are unknown for Group 2 of case studies, PGV parameter is considered as the closest parameter in content and concept to the SED which can be estimated for Group 2, using attenuation relationships. PGV values are drawn against SED (Figure 8-a) and SMV (Figure 8-b) for Group 1 of case studies. As it is indicated in these figures, PGV has a direct relationship with SED and SMV so that PGV values increase by increasing SED or SMV values. Therefore, it is expected that almost large amounts of PGV to be associated with high SED values and small amounts of PGV to be associated with low SED values. However, because of the unknown relationship between PGV and SED or SMV, it cannot be said that all of the medium PGVs can generate a medium SED. It seems that it depends on many unknown parameters such as the number of half-cycles, significant duration and etc. Therefore, a medium PGV can create a medium, a low or a high SED in various conditions. The PGV values for the case studies of Group 2 was calculated using mentioned procedure for obtaining response of sliding systems by attenuation relationship. PGV values for Group 2, are presented in table 6.

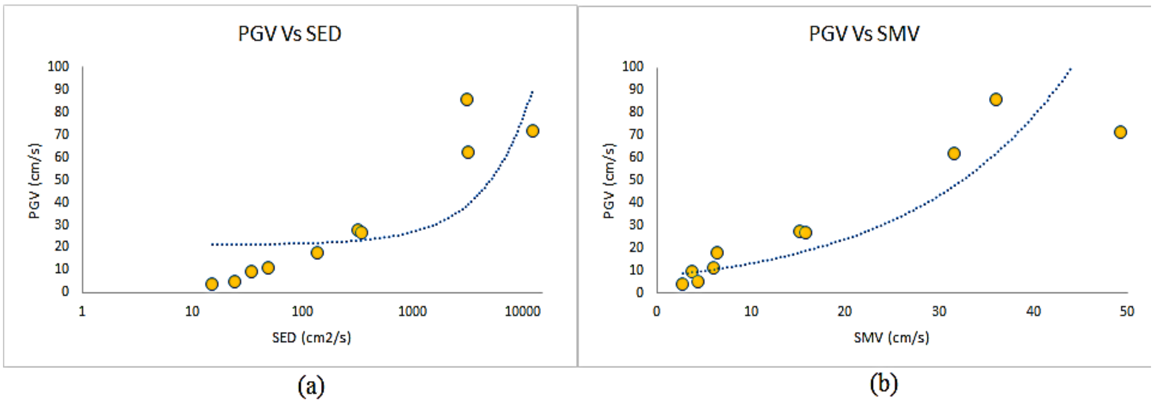

Figure 8. PGV versus energy representative parameters for Group 1 earth dams (a): PGV Vs SED / (b): PGV Vs SMV

Relative errors between observed deviatoric deformations of Group 2 and calculated deformation by upper bound of Bray and Travasarou [7] mmethod (designee method in this study) are depicted against PGV, in figure 9 using below equation:

$$\text{Relative Error (\%)} = \frac{D{,}calculated - D{,}observed}{D{,}observed} \times 100 \qquad (4)$$

Note that the vertical axis of figure 9 are relative error which are calculated by equation (4). It is obvious that the positive errors are related to the conservative results and the negative errors are related to the non-conservative results. Hence, the positive part of diagrams may gain a high value (For example > 100%) for a very conservative result while, the negative part of diagrams can have the maximum of 100% negative error when calculated deformation is equal to zero. Also, the horizontal axis of these figures are PGV which are calculated for each case using attenuation relationships as mentioned previously.

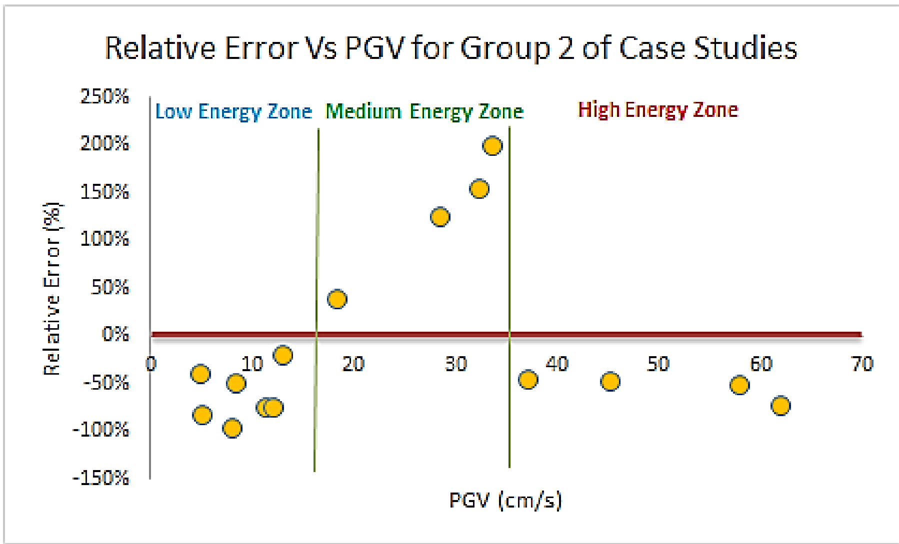

Figure 9. The relative errors of the upper bound values of Bray and Travasarou 2007 coupled-based method (the designee method), for estimating max deviatoric deformations versus PGV of the Group 2 case studies

As illustrated in figure 9, Bray and Travasarou [7] method (which is a non-linear coupled method) results in non-conservative predictions for small and large values of PGV which are related to low and high levels of energy respectively. On the other hand, this method results in conservative predictions only in the medium values of PGV. Although the figure 9 only depict the errors of max deviatoric deformation predictions, but this conclusion is also valid about max horizontal and max overall deformations.

It should be noted that although error values in low energy zone are larger than error values in high energy zone, but the absolute error values in high energy zone are larger. Therefore, as it is indicated in figure 10, not considering parameters related to energy concept in high energy zone is more critical. Note that the vertical axis of this figure is absolute errors which is calculated from equation (3) for Group 2 of earth dams, and the horizontal axis of this figure is PGV.

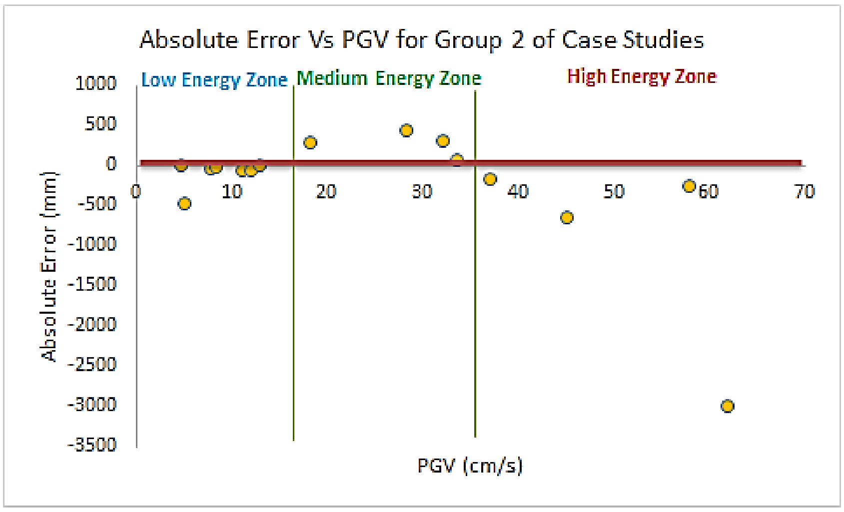

Figure 10. The absolute errors of the upper bound values of Bray and Travasarou 2007 coupled-based method (the designee method), for estimating max deviatoric deformations versus PGV of the Group 2 case studies

5. CONCLUSIONS

a. Applying all the 26 simplified and rigorous methods for 25 real Earth dams, it is observed that the method developed by Bray and Travasarou [22] which is a simplified non-linear coupled method, predicts the displacements better than other methods. This method has the highest number of acceptable (conservative) predictions and the lowest absolute values of negative error among all of the Newmark sliding block family methods. Note that also, while the method developed by Garini and Gazettas [15] has equal number of conservative predictions with this method, but the absolute values of negative error of Garini and Gazettas [15] method are higher than Bray and Travasarou [22] method. This means that when two methods result in the underestimated predictions, the Garini nd Gazettas [15] method is more non-conservative than the Bray and Travasarou 2007 method.

b. Energy representative parameters such as SED and SMV act as separator parameters so that the predictions of the methods are underestimated in the low and high levels of energy and also the conservative predictions of the methods occur only in the medium levels of energy.

c. It seems that energy has a key role in the occurrence of the permanent deformation of earthen structures so that the large values of observed deviatoric deformation of case studies occurred in large values of energy.

d. In conclusion, considering SED as an energy representative parameter may eliminate some errors of sliding block methods due to following observations:

- SED separates conservative and non-conservative deformation prediction using sliding block methods
- Some of important parameters such as PGV and SMVare included in SED content
- Deformation of earth dams increase by increasing SED values so that large values of permanent deformations occur in large values of SED. On the other hand, the cases with low and medium values of SED, experienced small values of deformations despite having wide range of Ky (between 0.06 and 0.32).

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