# Effect of preloading on the amplification of sand layers

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**SUMMARY:**
Preloading is a temporary loading, usually an embankment, applied to improve subsurface soils by densification. The paper studies the effect of preloading on the amplification characteristics of sandy sites with an elaborate parametric analysis. The soil type, the depth of the soil layer, the water table depth, the level of preloading and the applied earthquake were varied in a systematic manner. The analysis was performed by the commonly-used one-dimensional equivalent-linear dynamic method. The shear velocity versus depth and the effect of preloading on the shear velocity are computed with well-established soil mechanics equations. The results illustrated that the seismic response at the top of the layer generally decreases as a result of preloading. A more detailed analysis of results shows that the effect of preloading on the seismic response depends on the fundamental period of both the soil layer and the applied accelerogram. Based on the results, a method that a practicing engineer can apply to simulate the effect of preloading on the seismic motion is proposed.

*Keywords: preloading, sands, seismic motion, response spectra, maximum acceleration*

## 1. INTRODUCTION

Soft soil layers that are horizontal, or have a small inclination to the horizontal, run the risk of excessive ground settlement when constructions are applied. Furthermore, saturated loose sandy soils run the risk of liquefaction and excessive displacements under earthquakes. This displacement can cause serious damage and even collapse of buildings and other overlying structures. Contemporary international bibliography and design codes demand that the practicing engineer estimates ground settlement and if is not acceptable redisign his structure or improve the sub-soil. Furthermore, design codes demand that the factor of safety against liquefaction to be less than one and if is not to improve the sub-soil. Preloading is a temporary loading, usually an embankment, applied at a construction site to improve subsurface soils by densification and increased lateral stress. The method is frequently used to improve poor soil conditions and sustain large static loads (Stamatopoulos A. and Kotzias, 1985).

Most applications of preloading in the field, and relevant publications, consider the improvement of static properties of soil without, however, examining the corresponding effect in the dynamic response. The only previous work found in the literature examining the effect of preloading on the dynamic response was by Stamatopoulos and Aneroussis (2002). They considered a single site, where the shear velocity was measured both before and after preloading. Preloading was applied by an embankment 9m high (Stamatopoulos et al. 2005). According to standard practice, described in detail in the next chapter, an equivalent-linear one-dimensional analysis was performed. The results showed that the surface acceleration generally decreases with preloading, but the effect depends on characteristics of the applied motion.

The effect of preloading on the amplification characteristics of sandy sites has not been studied systematically. This is performed in the present article. Below, first the procedure of the analysis of the present study is given, as well as the cases considered. Then, the shear velocity and density versus depth for the different typical sand profiles are obtained based on state-of-the art relations of soil mechanics. The results and their analysis are given and, based on these a method that a practicing engineer can apply to simulate the effect of preloading on the seismic motion is proposed.

## 2. PROCEFURE OF ANALYSIS

In the present study the seismic response is calculated by the 1-dimensional equivalent-linear elastic method of analysis using the program EERA (Barbet et al., 2002), which is functioning at environment Windows EXCEL. The results of the programs were examined and it was confirmed that were identical to the SHAKE (Idriss and Sun, 1992) program. The parameters that must be defined and affect the solution are a) the location of the underlying rock, b) the velocity of the shear seismic waves Vs and the density of the soil, both versus depth c) the change in the shear modulus and the damping coefficient with the shear strain and d) the seismic motion applied at the bedrock and e) the shear velocity at the bedrock. The change in the shear modulus (G) and the damping coefficient (D) with shear strain ($\gamma$) was taken according to the largely used and validated G-$\gamma$ curves by Seed and Sun in 1989, and D-$\gamma$ curves by Idriss in 1990 (Kramer, 1996).

## 3. CASES CONSIDERED

The dynamic response of sands is affected by: (a) relative density, (b) stress level, that is affected by the locations of the water table, (c) the depth of the underlying rock, (d) the shear velocity of the underlying rock, (e) applied seismic motion and (f) the overconsolidation ratio, defined as

$$OCR = \sigma'_{v\text{-}max} / \sigma'_{v} \quad (1)$$

where $\sigma'_v$ is the current effective stress and $\sigma'_{v\text{-}max}$ is the maximum past effective stress.

In the present study (a) three types of sand that correspond to three relative densities: Dr 20%, 50% and 80% are considered. Regarding (b), the water table elevation is considered at two depths zw: 2 m and 10m. Regarding (c) different depths of bedrock are considered: db= 5, 10, 15, 20, 30, 45, 60m. Regarding (d), according to typical values of rock and standard practice, Vs equal to 1500m/s is assumed for the underlying rock. Regarding the applied motion the following 9 accelerograms were applied: Aegion, Friuli-xx, Friuli-yy, Kozani-xx, Umbria-xx, Halandri-xx, Halandri-yy, Kalamata x-x and Thessaloniki y-y. All earthquakes correspond to the recorded input motions, except from the Aegion earthquake where the decomvoluted motion is considered, as described by Stamatopoulos et al (2007). The reason is that the Aegion earthquake was recorded at the top of a soil stratum and had a very large horizontal maximum acceleration, equal to 0.5g, inconsistent to the current purpose of these motions in the current work, that is to apply them at the underlying bedrock. Table 1 gives the characteristics of the applied earthquakes. Fig. 1 gives the response spectra of the applied earthquakes. It can be observed that the applied earthquakes have an average maximum acceleration of 0.17g, an average maximum spectral acceleration of 0.60g and an average dominant period of 0.23s. These values are consistent with typical seismic motions at the underling bedrock (European Standard, 2003) Table 2 gives the soil profiles considered.

The overconsolidation ratio (OCR) is varied in order to investigate the effect of preloading. Preloading is applied, as usually in practice, as an embankment that is placed temporarily at the top of the soil. It is assumed that the embankment has big length, so that plane strain conditions exist. In particular, for the case without preloading, it is assumed that the soil has OCR=1. This case corresponds to an embankment with preload zero height. Two other cases of preloading are assumed with embankment height 5 and 11m. Fig. 2 gives schematically the cases considered.

It is inferred that the cases considered, i.e. the dynamic analyses that were performed, are 3X2X6X7X9X3=3402. Furthermore, the cases considered at each preload case are 1133 and the cases considered for each earthquake motion are 378.

**Table 1.** Characteristics of earthquakes considered

| No | Name | Comp | M | $a_{max}$ (g) | $T_{cr}$ | $S_{amax}$ (g) | Comment |
|---|---|---|---|---|---|---|---|
| 1 | Aigion 15/6/1995 | xx | 6.34 | 0.17 | 0.41 | 0.61 | Decomvoluted at the bedrock |
| 2 | Friuli-San | xx | 5.98 | 0.14 | 0.15 | 0.44 | - |
| 3 | Rocco 15/9/76 | yy | | 0.23 | 0.19 | 0.73 | - |
| 4 | Kozani 13/5/1995 | xx | 6.51 | 0.20 | 0.23 | 0.66 | - |
| 5 | Umbria 29/4/1984 | xx | 5.38 | 0.20 | 0.15 | 0.89 | - |
| 6 | Athens - Chalandri | xx | 5.9 | 0.11 | 0.13 | 0.41 | - |
| 7 | 7/9/1999 | yy | | 0.17 | 0.20 | 0.58 | |
| 8 | Kalamata 13/6/1986 | xx | 6.2 | 0.21 | 0.28 | 0.64 | |
| 9 | Thessaloniki 20/6/1988 | xx | 6.5 | 0.13 | 0.30 | 0.48 | |
| | Average | | | 0.17 | 0.23 | 0.60 | |

**Table 2**. Types of soil profiles considered in the present study

| No | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Dr | 0.2 | 0.5 | 0.8 | 0.2 | 0.5 | 0.8 |
| water table depth (m) | 2 | 2 | 2 | 10 | 10 | 10 |

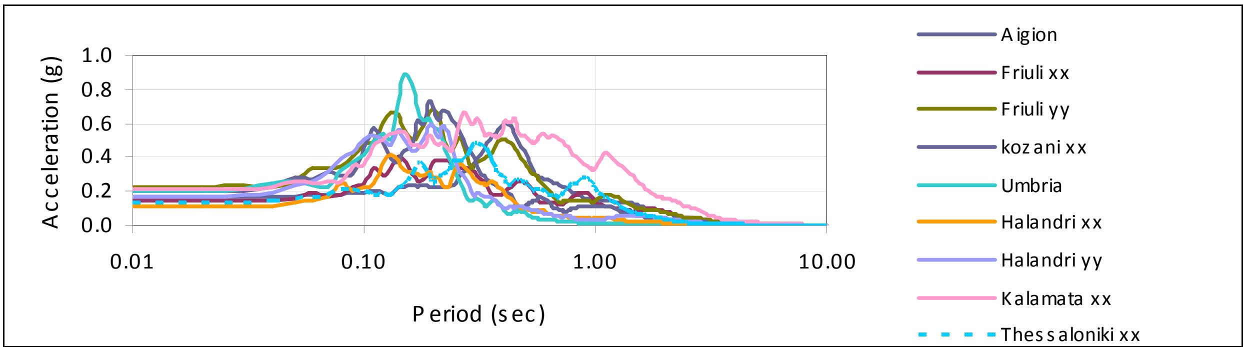


**Figure 1.** Response spectra of applied accelerograms

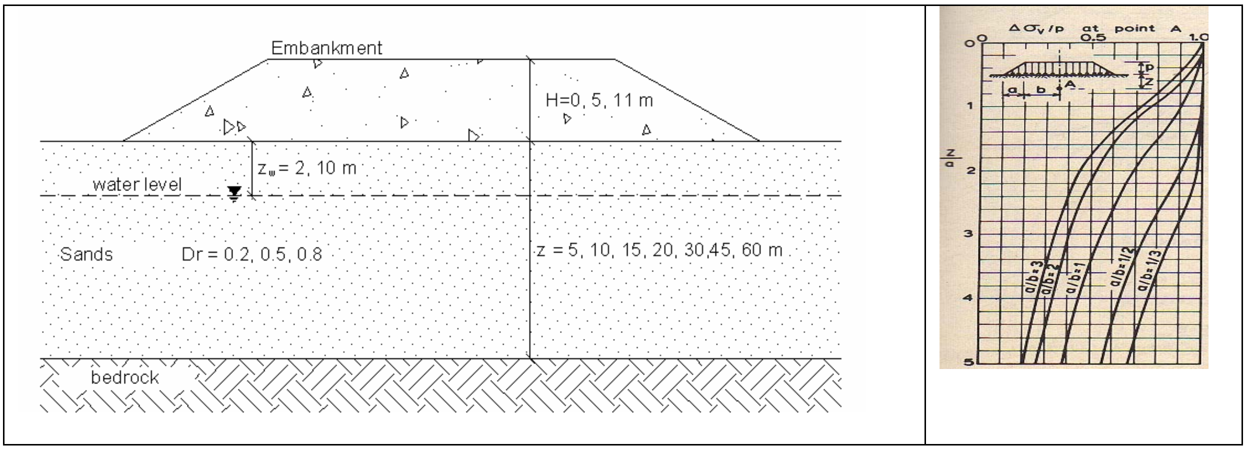


**Figure 2.** Schematic illustration of cases considered and vertical stress induced by the embankment versus depth, according to linear elasticity theory.

## 4. THE SHEAR VELOCITY AND DENSITY VERSUS DEPTH

For the analysis of the seismic response of soils the most important parameter that affects the results considerably is the elastic shear velocity, Vs, that can be estimated form the shear modulus at small strains, $G_{max}$ and the soil unit weight, $\gamma$, and the acceleration of gravity, g, as ($Vs = (gG_{max}/\gamma)^{1/2}$). According to Kramer (1996), for sands the most complete equation that predicts $G_{max}$ is

$$G_{max}=625\ (1/e^{1.3})\ Pa\ (\sigma'_{oct}/Pa)^{0.5} \quad (2)$$

where Pa is the atmospheric pressure, $\sigma'_{oct}$ is the effective octahedral stress . The octahedral effective stress $\sigma'_{oct}$ can be expressed as

$$\sigma'_{oct}= (1+2k_o)\ \sigma'_v \quad (3)$$

where ko is the lateral effective stress coefficient. The empirical relationship by Mayne and Kulhway (1982) relates the factor $k_o$ with the OCR and the maximum friction angle ($\varphi'$) as:

$$k_o = (\sigma'_h / \sigma'_v) = (1 - \sin\varphi')\ OCR^{\sin\varphi'} \quad (4)$$

For sands, according to Bolton (1986) the maximum friction angle can be obtained in terms of the relative density (Dr) and the steady-state friction angle, $\varphi'ss$ as

$$\varphi'= \varphi'ss + 3\ [\ (Dr/100)\ (10-\ln \sigma'_{oct}\ )-1] \quad (5)$$

The friction angle, $\varphi'ss$, does not vary considerably from sand to sand and a typical value is 30$^o$ (Bolton, 1986). The effective stress above the water table are estimated as

$$\sigma'_v = \gamma_d\ z \quad (6)$$

where z is the depth and the dry unit weight of the soil equals

$$\gamma_d =2.7\ g\ /\ (1+e) \quad (7)$$

where g is the acceleration of gravity. Below the water table the effective stress is estimates as

$$\sigma'_v = \gamma_t\ z - 10\ \gamma_w\ (z - z_w) \quad (8)$$

where $z_w$ is the depth of the water table line, $\gamma_w$ is the unit weight of the water and $\gamma_t$ is the total unit weight that equals

$$\gamma_t= 2.7\ g\ (1+ 2.7\ e)\ /\ (1+e) \quad (9)$$

For sands, the void ratio can be estimated in terms of relative density as

$$e = e_{max} - Dr\ (e_{max} - e_{min}) \quad (10)$$

A typical value of $e_{max}$ and ($e_{max} - e_{min}$) equals 0.90 and 0.36 respectively. Thus, equation (9) becomes

$$e = 0.90 - 0.36\ Dr \quad (11)$$

The coefficient of compressiblility (Cc) of sands does not depend on the relative density considerably and a typical value of Cc for sands is 0.1 (Modaressi and Caballero, 2001, Stamatopoulos, 2003). Thus, as a result of preloading, the void ratio of sands equals

$$e = 0.90 - 0.36\ Dr - 0.1\ \log\ (OCR) \quad (12)$$

The maximum effective stress, as a result of the preload embankment $\sigma'_{v-max}$ , that affects OCR, is estimated as

$$\sigma'_{v-max}= \sigma'_v+\sigma'_{v-prel} \quad (13)$$

where $\sigma'_{v\text{-}prel}$ is the vertical stress induced by the preload embankment, that can be estimated from the theory of elasticity (Stamatopoulos and Kotzias, 1985), as indicated in Fig. 2, assuming that a/b=1.

Combination of equations (1)-(13) can predict $G_{max}$ , or equivalently Vs, versus depth for all cases considered in the present study. The shear velocities versus depth estimated for all cases considered, are given in Fig. 3. One meter sub-layers were used for this purpose. From the Shear velocity versus depth profiles, the dominant periods of the layers considered, that affect the seismic response, are given in Fig. 4.

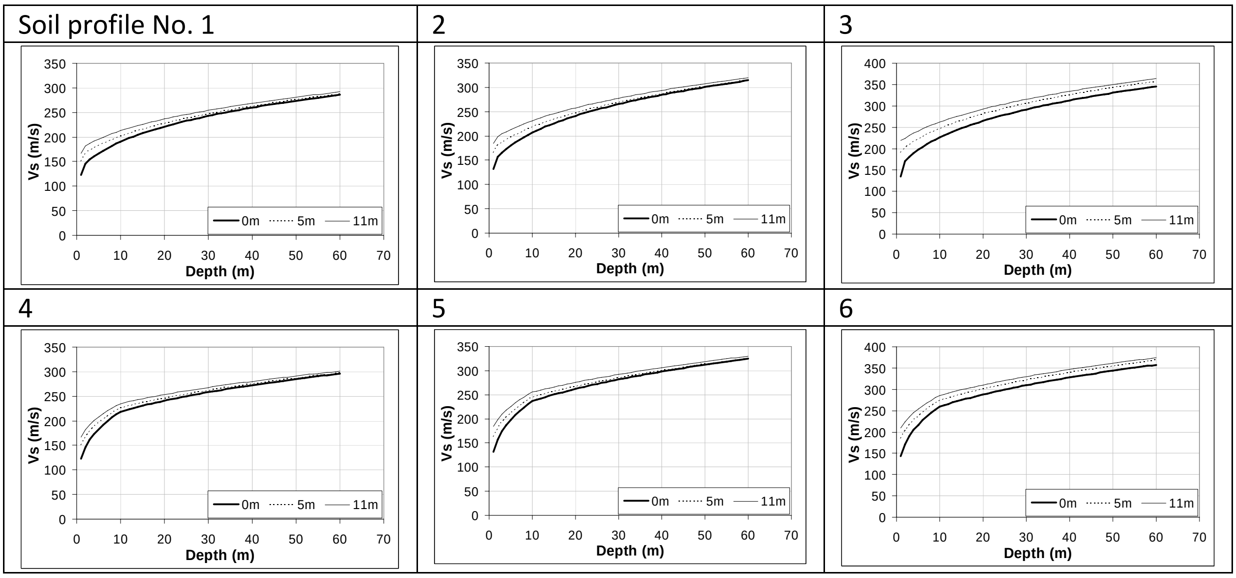


**Figure 3.** The Shear velocity versus depth in terms of height of preload and soil profile type.

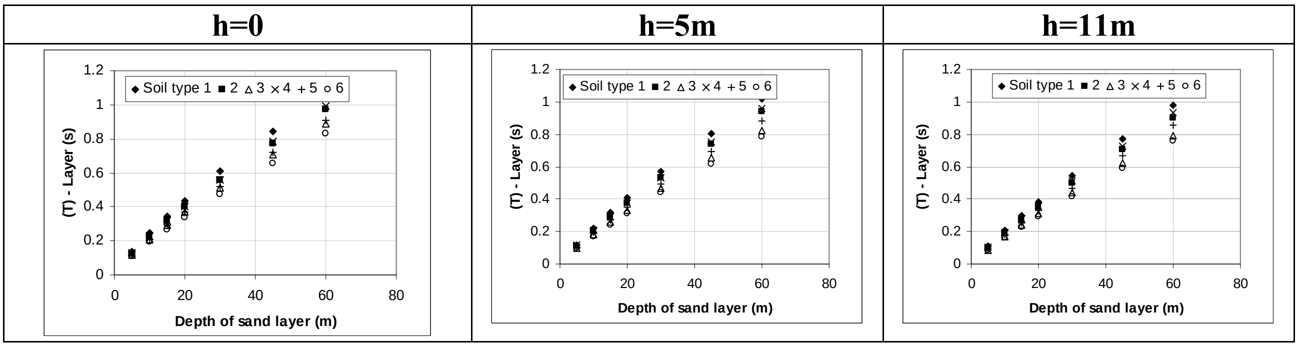


**Figure. 4**. Dominant periods of the layers considered in terms of the preload height (h).

## 4. RESULTS AND THEIR ANALYSIS

For the procedure of dynamic analyses described above, for each case described above the response spectrum of the seismic motion at the ground surface was recorded. The response spectra illustrate many critical aspects of soil response. In particular, (a) the maximum acceleration ($a_{max}$), the maximum spectrum acceleration ($Sa_{max}$) and the period corresponding to the maximum spectral acceleration (Tcr) are important parameters of the seismic motion that affect overlying structures, and were recorded. Typical results are given in Fig. 5. Spectra responses in terms of the height of the preload embankment (h) are given for the case of soil profile 3, the Aegion earthquake and depth of bedrock db=5m, 20m and 60m.

Prior to investigate the effect of preloading, the computed seismic response is studied. Table 3 gives the average and the standard variation of the computed values of ($a_{max}$), ($Sa_{max}$) and (Tcr) for all cases considered. Fig. 6 gives the ratios $a_{max}/a_{max\text{-}base}$ and $Sa_{maxp}/Sa_{max\text{-}base}$ in terms of the ratio $R=T_s/T_{cr\text{-}motion}$, where $T_s$ is the fundamental period of the soil profile and $T_{cr\text{-}motion}$ is the critical period of the applied motion, for all cases considered. It can be observed that $a_{max}/a_{max\text{-}base}$ and $Sa_{map}/Sa_{max}$ (a) tend to one when R tends to zero, (b) take their maximum values when R equals to unity and (e) equal to about 2 as R is greater than about 2. These are consistent with what seismic response theory of soil layers (Kramer, 1996, Idriss, 1990, European Standard, 2003) predict: (i) the seismic response is amplified when resonance exists, (ii) the amplification of the seismic motion equals to about 2 for $a_{rock}$=0.17g, that is the mean value in the present case, $a_{soil}$=0.3g and (iii) the amplification of $a_{max}$ does not differ considerably from the amplification of $Sa_{max}$ for given soil type.

To investigate the effect of preloading in the factors ($a_{max}$), ($Sa_{max}$) and (Tcr), a linear percentage change of these parameters is assumed in terms of the preload height, h. In particular, it is assumed that

$$\begin{aligned} a_{\max} / a_{\max\text{-}h=0} &= A_a\, h + 1 \\ Sa_{\max} / Sa_{\max\text{-}h=0} &= A_{Sa}\, h + 1 \\ Tcr / Tcr_{h=0} &= A_T\, h + 1 \end{aligned} \qquad (14)$$

where h is in m and $A_{Sa}$ , $A_T$ and $A_a$ are factors. The coefficient of correlation of the three expressions is represented as $R_{Sa}^2$, $R_T^2$, $R_a^2$ respectively. For each case, the factors $A_i$ illustrate the effect of the preload height of the dynamic response, while the coefficient of correlation $R_i^2$ illustrates the precision of equations (14) to predict the effect of preloading.

Figure 7 gives the estimation of the factors Ai for the three typical cases of Fig. 5. Due to space limitations, the $A_i$ and $R_i^2$ factors computed for all cases are not given. However, Table 4 gives the statistical analysis of these factors. As the average value of all $R_i^2$ is greater than 0.7, it is inferred that the form of equation (14) is reasonable. In addition, the fact that $A_T$ is in negative is consistent with the theory of the seismic response of soil layers: As a result of preloading, the period of the layer, $T_{layer}$, decreases. Thus, the period of $S_{amax}$ must also decrease and the factor $A_T$ must be negative. In particular, the theoretical variation of $A_T$, based on the change of the period of the layer, given in Fig. 4, corresponds to an A value that varies from -0.01 to -0.04, that is in general agreement with the computed values of $A_T$, that have an average value of -0.01 and a standard deviation of 0.01.

Regarding the parameters $A_{Sa}$ and $A_a$ , these will be considered together, as they both describe the change in the intensity of the seismic response. From table 4, it is observed that they are negative, with an average value of -0.01. Furthermore, their dependence on the factor $R=T_{layer}/T_{cr\text{-}motion}$ is investigated. The reason is that, as illustrated in Fig. 6, the seismic motion is amplified when the ratio R equals about unity. Furthermore, as described in Fig. 5 and above, preloading affects $T_{layer}$. Thus, it is anticipated that the parameters $A_{Sa}$ and $A_a$ may be affected by the factor R.

Fig. 8 gives the parameters $A_{Sa}$ and $A_a$ in terms of the factor R. It is observed that (a) When R is less than unity, $A_{Sa}$ and $A_a$ are negative for almost all cases, (b) When 2>R >1, $A_{Sa}$ and $A_a$ are both positive and negative. (c) When R >2, $A_{Sa}$ and $A_a$ are negative in almost all cases. These are consistent with what seismic response theory of soil layers predicts: As a result of preloading, according to Fig. 4, $T_{layer}$ decreases by as much as 0.1s in some cases. Thus, as $T_{motion}$ can be as small as 0.13s, preloading can decrease the ratio $R=T_{layer}/T_{cr\text{-}motion}$, even from 1 to about 2. It is inferred, that at the range 2>R >1, as a result of preloading, $A_{Sa}$ and $A_a$ may increase, unlike the other ranges of R. Table 4 gives in detail the statistical analysis of the numerical results regarding Aa and ASa in terms the above ranges of the factor R.

**Table 3.** The average value and the standard deviation of $a_{max\text{-}tap}/a_{max\text{-}base}$, $Sa_{max\text{-}tap}/Sa_{max\text{-}base}$, $T_{cr}$ for all cases considered

| $a_{max\text{-}tap}/a_{max\text{-}base}$ | | $Sa_{max\text{-}tap}/Sa_{max\text{-}base}$ | | Tcr (s) | |
|---|---|---|---|---|---|
| Ave | stdev | Ave | stdev | Ave | stdev |
| 2.0 | 0.46 | 2.36 | 0.84 | 0.30 | 0.21 |

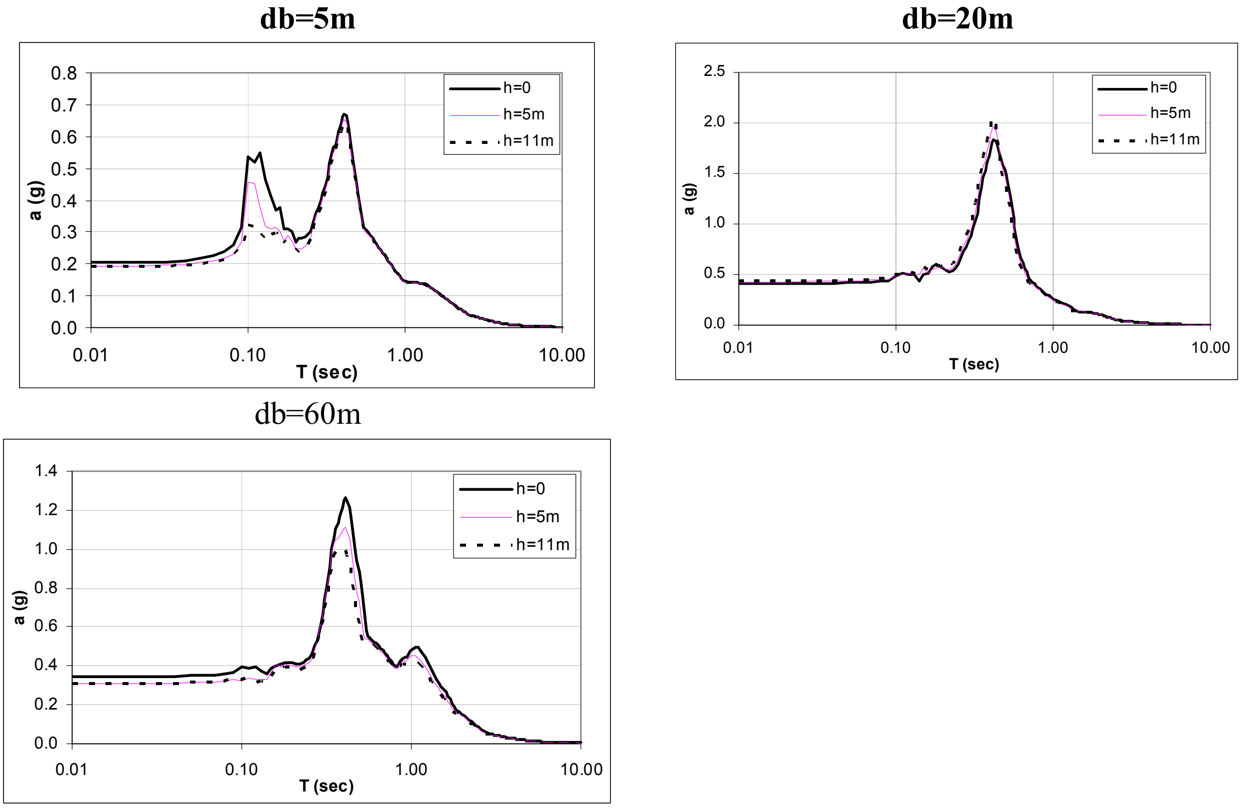


**Figure 5.** Typical results. Spectra responses in terms of the height of the preload embankment (h). The case of soil profile 3, the Aegion earthquake and depth of bedrock db=5m, 20m and 60m are given.

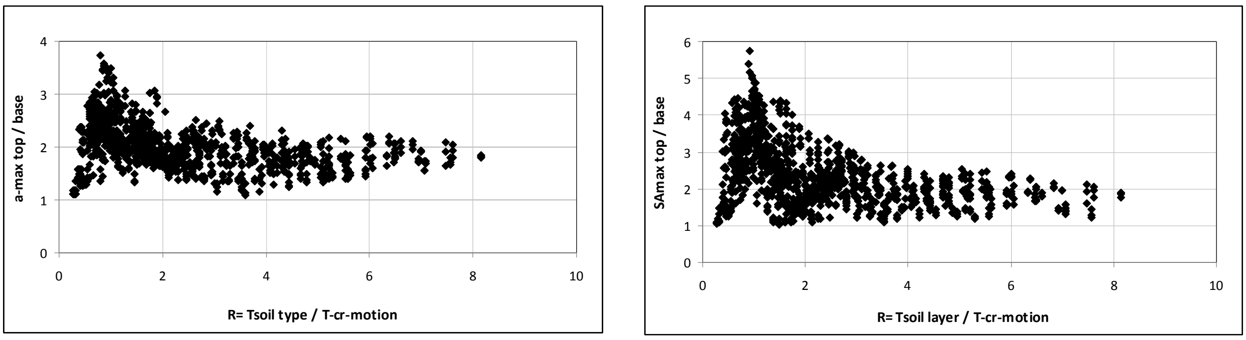


**Figure 6**. The ratios $a_{max-tap}/a_{max-base}$ and $Sa_{max-tap}/Sa_{max-base}$ *in terms of the ratio R=Tsoil layer/T-cr-motion* for all cases considered.

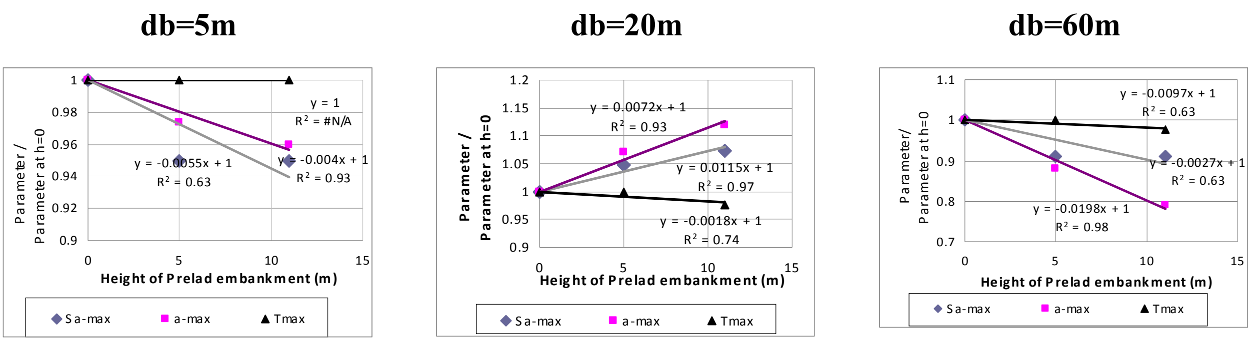


**Figure 7.** Typical results of analysis. The factor A. The case of Fig. 5 is given.

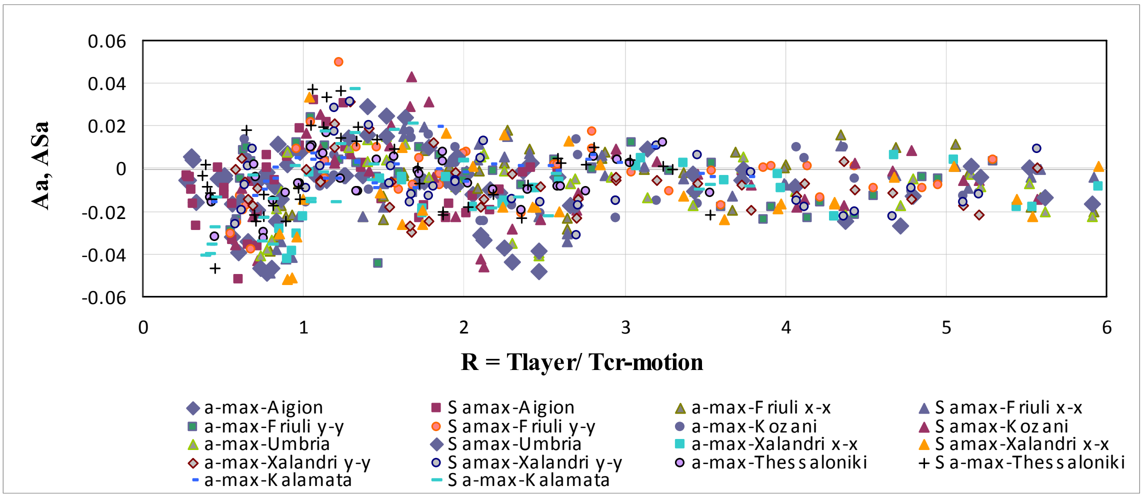


**Figure 8.** The parameters $A_{Sa}$ and $A_a$ in terms of the ratio $R=T_{layer}/T_{motion}$.

**Table 4.** Statistical analysis of the factors A.

(a) All cases

| | $A_a$ | $A_{Sa}$ | $A_T$ |
|---|---|---|---|
| $R^2$ ave | 0.75 | 0.73 | 0.76 |
| ave | -0.01 | -0.01 | -0.01 |
| std | 0.01 | 0.02 | 0.01 |
| max | 0.03 | 0.05 | 0.05 |
| min | -0.05 | -0.05 | -0.08 |

(b) in terms of $R=T_{layer}/T_{cr\text{-}motion}$.

| | R <1 | | 1< R <2 | | R >2 | |
|---|---|---|---|---|---|---|
| | $A_a$ | $A_{Sa}$ | $A_a$ | $A_{Sa}$ | $A_a$ | $A_{Sa}$ |
| ave | -0.01 | -0.02 | 0.00 | 0.01 | -0.01 | -0.01 |
| std | 0.01 | 0.02 | 0.01 | 0.02 | 0.01 | 0.01 |
| max | 0.02 | 0.03 | 0.03 | 0.05 | 0.02 | 0.02 |
| min | -0.04 | -0.05 | -0.04 | -0.03 | -0.04 | -0.05 |

## 5. DISCUSSION

In practice, in a given region, the properties of the soil profile, and equivalently, $T_{layer}$ are known, or can me determined from a geotechnical investigation. However, $T_{cr\text{-}motion}$ is not known apriori. Thus, the values of table 4b cannot be applied directly. On the other hand, as $T_{cr\text{-}motion}$ varies in a given range (0.1 to 0.4s typically in Europe), it is inferred that a relationship can be obtained between the depth of the soil layer and the $A_{Sa}$ and $A_a$ factors. In particular, sandy layers with depth less than 5m correspond to case R<1, while sandy layers with depth greater than 50m correspond to the case R>2, while sandy layers with depth between 10 and 50m can correspond to all cases of variations of R

Fig. 9 gives the parameters $A_{Sa}$ and $A_a$ in terms of the depth of the soil layer and the applied earthquake. The mean value and standard deviation of the results are also given. Based on Fig. 9 and table 4, proposals for the factors A for design are given in table 5. For regular projects the mean values of the factors A of table 5 should be used. For projects with major importance the mean plus standard deviation values of the factors A of table 5 should be used, or alternatively, numerical dynamic analyses using the existing local soil conditions should be used to estimate the factors A for this particular case.

Based on all the above, the following can be proposed to analyze the effect of preloading on the seismic motion at the top of sandy layers, when the dominant period of the applied motion is known and dynamic analyses are not performed: (a) Based on the geotechnical profile, estimate the factors A according to table 5. (b) Based on the factors A and the height of the preload embankment, estimate the effect of preloading on the seismic motion.

The proposed work considered homogenious soil conditions of given relative density. More work is needed to verify that the proposed method can apply for non-homogenious soil conditions.

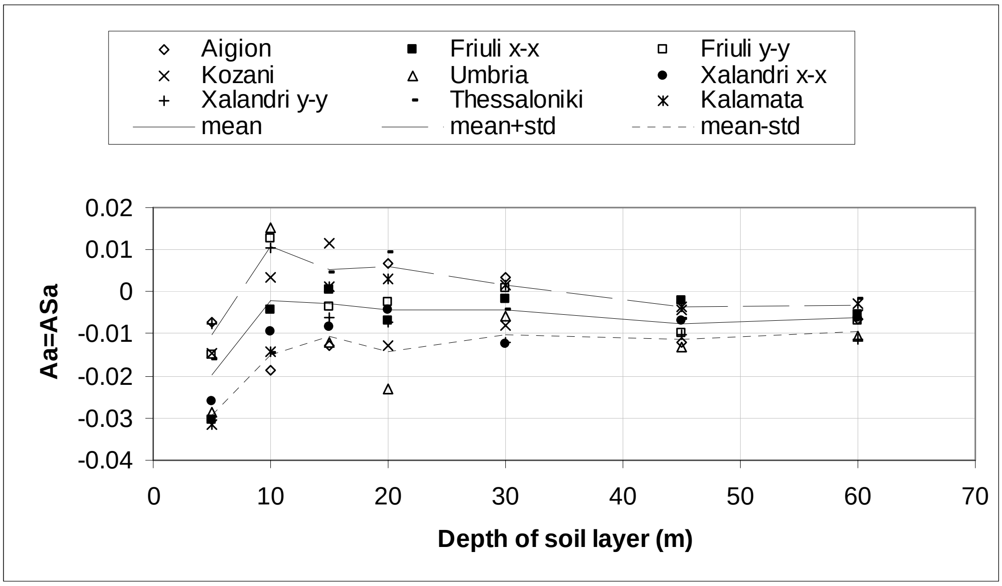


**Figure 9.** The parameters $A_{Sa}$ and $A_a$ in terms of the depth of the soil layer. The standard deviation of the results are also given.

**Table 5**. Proposals for the factors A for design.

| | $A_T$ | $A_a$ , $A_{Sa}$ | | |
|---|---|---|---|---|
| | | Depth of soil < 7.5m | 7.5m < Depth of soil < 35m | Depth of soil > 35m |
| Mean | -0.01 | -0.01 | -0.003 | -0.005 |
| Mean+Std | 0 | 0 | 0.005 | -0.003 |

## 6. CONCLUSIONS

The paper studies the effect of preloading on the amplification characteristics of sandy sites with an elaborate parametric analysis. Different relative densities, water table depths, bedrock depths and levels of preloading were considered. Pre- and post-preloading shear velocity profiles were based on empirical relationships that have been proposed in soil mechanics. The dynamic analyses performed were 1-dimensional equivalent-linear, typically used in earthquake geotechnical engineering. The maximum acceleration ($a_{max}$), the maximum spectrum acceleration ($S_{amax}$) and the period corresponding to the maximum spectral acceleration (Tcr) are important parameters and were recorded and analyzed. To investigate the effect of a preloading embankment in these factors, a linear percentage change of these parameters is assumed in terms of the preload height, by the factors ASa , AT , Aa, defined by equations (14).

As the factors ASa and Aa both describe the amplification of the seismic motion induced by preloading, they are considered together. Preloading, as it increases the shear velocity of the stratum, decreases its fundamental period and thus should decrease also the critical period of the spectral response. Indeed, the parametric analyses illustrated that $A_T$ has a value $A_T$=-0.01+/-0.01. On the other hand, it was observed that the factors ASa and Aa depend on the characteristics of both the layer and the applied accelerogram. Indeed, it was observed that the factor R, defined as the ratio Tlayer/Tcr-motion, affects critically the factors ASa Aa (table 4b) .

In practice, in a given region, the properties of the soil profile, and equivalently, $T_{layer}$ are known, or can me determined from a geotechnical investigation. However, $T_{cr\text{-}motion}$ is not known apriori. Thus, the values of table 4b cannot be applied directly. On the other hand, as $T_{cr\text{-}motion}$ varies in a given range (0.1 to 0.4s typically in Europe), it is inferred that a relationship can be obtained between the depth of the soil layer and the $A_{Sa}$ and $A_a$ factors. Fig. 9 gives the parameters $A_{Sa}$ and $A_a$ in terms of the depth of the soil layer and the applied earthquake. Based on Fig. 9 and table 4, proposals for the factors A for design are given in table 5. For regular projects the mean values of the factors A of table 5 should be used. For projects with major importance the mean plus standard deviation values of the factors A of table 5 should be used, or alternatively, numerical dynamic analyses using the existing local soil conditions should be used to estimate the factors A for this particular case.

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