A Numerical Investigation on the Effect of Angle and Initiation Point of Slope on the Base Flexural Moment in Seawalls under Random Waves

Ramin Vafaeipour Sorkhabi
Department of Civil Engineering, Tabriz Branch, Islamic Azad University, Tabriz, Iran
Afshin Abasi
MS student of Hydraulic Structure, Ahar Branch, Islamic Azad University, Ahar, Iran
Omid Giyasi Tabrizi (Corresponding Author)
BS student of Civil Engineering, Tabriz Branch, Islamic Azad University, Tabriz, Iran

Abstract: Seawalls are one of the most important types of sheltering structures which are constructed along the coast line. The main exerted force on these structures is the random sea wave induced load during the storm conditions. In such conditions, free surface of the water has a time dependent irregular pattern which can be described by either a time series or an energy spectrum. The wave induced pressure on a seawall is random in nature and consequently, the internal forces produced in the body of the structure have a random temporal change. The internal forces can be minimized through changing the slope of the seawall in an either local or global sense. In order to study the effect of slope's characteristics on the wave induced internal forces, a number of seawalls with different slope angles on their upper part have been modeled and analyzed subjected to sea waves, using the SACS software package. In the considered models, the wall is vertical between the base and the initiation point of the slope at the wall's upper part. Different values have been assigned to the slope of the seawall with the increments of 5˚ ranging from 0˚ to 45˚ with respect to the vertical axis. Different positions have also been considered for the initiation point of the slope with the increments of 5 cm. The first position is at the base and the last one is at the surface of the wave. In order to increase the accuracy of results, the structure's weight and the hydrostatic pressure have been considered during the analysis. The results show that when the initiation point of the slope is at the distance of half of the significant wave height from the water surface and the angle of the slope is 35˚, the base flexural moment becomes minimized and increase of the slope beyond this value will be no longer effective in minimizing the moment.

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1. 1. Introduction

Seawalls design and make to coastal protection against waves and to prevent entering water to coasts and in order to proper use of coastal lands. In order to optimize design in coastal engineering must be have appropriate information about exerted loads and coastal structural behavior against these loads. The important exerted loads on the seawalls are sea waves that certainly would be the most severe under storm conditions. The main hydrodynamic parameters include wave height, period and length. Due to random behavior of the wave, cannot be defined precisely the coastal structural behavior just rely on the theory. Therefore, in these cases using from authentic software and laboratory studies will be important. Due to wall base moment in seawall design is one of the most influential factors so set it when radiate random waves will be contributed to the design (Goda, 2000). Implement vertical walls are easier than steep walls and takes up less area of costal lands. Length of the wall is less so its weight is less. On the other hand due to vertical position of wall, its weight will be on base, so the weight flexural moment will be zero relation to the base. Also because of high reflection it does not exist on the wave. During collision wave and its reflection, wave force and follow base flexural moment increases. And this is one of the negative sides of these walls against the mentioned advantages. In steep walls because of wave energy dissipation during the collision, exerted force of the wave on structure is reduced significantly. In such case, base flexural moment caused by wall weight, water weight on the wall and wave induced force. On this basis, can be examined dual steep wall. In this case the wall will be vertical from base to starting point of slope and from that point to top of the wall is considered steep. Because of bulk of the wave induced forces on structures occurs near water surface, using these walls cause reduce base flexural moment result of wave induced , structure weight and water weight. It seems walls with dual slope had vertical and steep walls advantages together. In this context, determine starting point of slope on the wall will be important in order to achieve minimum flexural moment. Due to waves random behavior would require a lot of trial and error to reach slope starting point and slope angle. Therefore, use reliable software in this field such as SACS software will be useful.

1.1 A Review of Experienced Researches

Many seawalls across the world due to lack of sufficient precision in design have caused great damage. Many of these faults occur because of structural collapse, crack in weak areas and total slide (Minkin, 1963). Hydrodynamic pressure distribution is high in water level and decreases in depth. However, hydrostatic pressure resulting from contact with the wall in rest condition is zero at water level but increases linearly in water depth. Sum of these two pressures is total pressure exerted on the wall. Due to maximum value of the hydrodynamic pressure occurs at the surface, also, because of arm length to the base approximate equality with water depth, flexural moment resulting from hydrodynamic pressure would be considerable (SPM, 1984). The wave's hydrodynamic pressure is a function of reflection coefficient. Reflection usually occurs in walls with low slope and nearly vertical. Reflection coefficient will be close to one and in this case the waves are non-breaking. But in walls with high slope, Cr is near zero and wave is kind of breaking mode also, in intermediate state, the wave will break (SPM, 1984; Neelamani et al., 1999).

$$\left[C_r = \frac{H_r}{H_i}\right]$$

Where:

H_r: is returning wave height in front of the structure.

The first studies were done to design seawall by Sainflou in 1928. He presented simple wave theory for calculation of wave's hydrodynamic performance on smooth vertical walls. The studies were completed with laboratory studies by Rundgren in 1958. Equations 2 and 3 offer Sainflou equations for calculation of non-breaking waves on vertical walls (Neelamani et al., 1999; Cheghini, 1998).

$$p_1 = \frac{1+C_r}{2}.\frac{\rho g H_i}{\mathrm{Cosh}\left(\frac{2\pi\pi}{L}\right)}$$

$$M = M_s + M_{wave} = \frac{1}{6}\rho g h^3 + M_{wave}$$

In above equations ρ is water density, h the water depth in front of a wall, g gravity acceleration, L wavelength and M_s moment result of water hydrostatic force, M_{wave} moment result of radiation,p_1 excess pressure during collision wave with its peak point and M total base flexural moment. To obtain M_{wave} can be use the diagrams provided by Rundgren. MiniKin theory has been represented in 1963 based on empirical observations about large walls for breaking waves (Minkin, 1963). Goda represent the basic theory of wave's effect on seawall in 1974 .The theory today widely used in design of seawall. Shuto presented two-dimensional wave theory to calculate two-dimensional waves induced force in 1972, using Lagrange theory. This theory can be offer base moment either in breaking or non-breaking conditions (Neelamani et al., 1999). Interaction numerical studies between wall and waves have done by Ahrens in 1993 also, by Vander Meer in 1955 and Schutrumpf and et.al in 1994 to investigate waves exerted force (SPM, 1984; Cheghini, 1998). Based on the theory can be said many studies don't on the steep walls. Two-dimensional wave theory is expressed based on equations 4 to 7 about flat steep walls in position two-dimensional regular waves (Figure 1). Neelamani and Sandhya saw large errors between experimental and theoretical results by laboratory studies on steep walls in 2005.

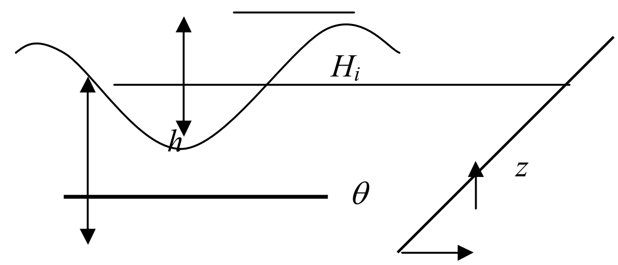

Figure 1: Wave impact on Steep walls

$$P(x,z,t) = \frac{1}{2}\rho g H_i \frac{\cosh(kz)}{\cosh(kh)}\cos(kx-\omega t) + \frac{1}{2}\rho g H_r \frac{\cosh(kz)}{\cosh(kh)}\cos(kx+\omega t+\gamma)$$

$$P(x,z,t) = \frac{1}{2}\rho g H_i \frac{\cosh(kz)}{\cosh(kh)}\sqrt{1+C_r^2+2C_r\cos(2kx+\gamma)}\cos(\omega o-\alpha)$$

$$\alpha = \mathrm{Arctan}\,\frac{\sin(kx) - C_r\sin(kx+\gamma)}{\cos(kx) + C_r\cos(kx+\gamma)}$$

$$P_{max}(x,z) = \frac{1}{2}\rho g H_i \frac{\cosh(kz)}{\cosh(kh)}\sqrt{1+C_r^2+2C_r\cos(2kx+\gamma)}$$

In above relations (x,z) is steep wall local coordinates in horizon and vertical sides, k= $\frac{2\pi}{L}$ wave number, wave length, $\omega = \frac{2\pi}{T}$ wave angle frequency and T is wave period. P(x,z,t) is Pressure distribution on seawall at any time and p_{max} (x , z) is maximum pressure on wall and γ is wave phase due to wave reflection. Muni Reddy used submerged breakwaters in order to reduce the impact of waves on seawall in front wall in 2005 and observed reduce its impact based on the height of the submerged breakwater relation to wall height (Muni Reddy and Neelamani, 2005). Jeng used porous submerged breakwaters in front of the wall like as Muni Reddy in 2005(Jeng et al., 2005). Zanuttigh studied impact a variety of materials used on wall to reduce wave effects in 2005 (Zanuttigh and Vander Meer, 2008).

Pullen et al., 2009, Studied using precision measuring instruments, amount bending on Walling ford seawall in Edinburgh. In 2010 Cuomo done extensive experimental studies on a gentle slope wall encountering with random waves (Cuomo et al., 2010a,b) and in 2010 Ahand et al., investigated effect of random waves on curved walls numerically. Despite were done extensive researches on seawall about substantial impact of steep wall particularly double steep walls according to present authorś information did not research to determine wave random induced force using updated software, especially SACS software.

1.2 Waves on the seawall

In general, waves were classified into waves regular and random. Random waves can be defined by combining infinite regular waves. During the storm condition, sea waves are kind of random waves and the water level is irregular. Using spectral analysis on recorded signals can be studied random waves. In this regard, by spectral density can be expressed a comprehensive explanation of the radiated waves during different sea conditions (Design regulation of Marine Structures, 2006). Based on recorded data, different spectrums such as Bretschnider spectrum in 1959, P-M spectrum in 1964 , TMA spectrum in 1985 and JONSWAP spectrum in 1974 have been defined (Sorensen, 1993; SACS, 2005; Cheghini, 1998). Sorensen has been introduced JONSWAP spectrum as one of the best spectrum to design seawalls (Sorensen, 1993; Ichikawa et al., 2010). In this study used JONSWAP spectrum.

1.3 JONSWAP spectrum

Obtained results from studies in the North Sea, allowing a proper estimation of limited one-dimensional wave spectrum. Figure 2 shows the spectrum. In this figure the horizontal axis, show wave frequency (f) and vertical axis show wave spectral density changes S(f) that are expressed by equations 8 to 11.

$$S(f) = \frac{\alpha g^2}{(2\pi)^4 f^5} e^{-1.25\left(f_p/f\right)^4} \gamma^a$$

$$a = e^{-\left[\left(f-f_p\right)^2/\left(2W^2 f_p^{\,2}\right)\right]}$$

$$\alpha = 0.076\left(\frac{gF}{U^2}\right)^{-0.22}$$

$$f_p = \frac{3.5g}{U}\left(\frac{gF}{U^2}\right)^{-0.33}$$

In this spectrum γ coefficient is between 1/6 to 6 but number 3/3 is recommended. γ coefficient is density ratio in the maximum frequency for JONSWAP spectrum against P-M spectrum. f_p is frequency of spectral peak ,F wave length and U is wind speed in 10 m level. Per $f \leq f_p$, W=0.07 and per $f > f_p$, W=0.09 are considered. Figure 2 is obtained based on wave length 30 km and wind speed 40 knots (Design regulation of Marine Structures, 2006).

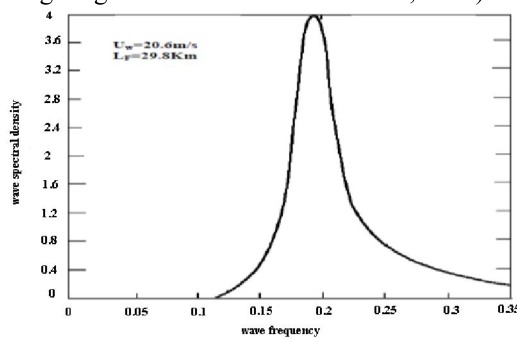

Figure 2: JONSWAP wave spectrum [16]

2. Methods

In this study, model of a steel seawall with dimensions 1 m × 1/5 m and thickness 1 cm has been considered which is free in floor and sides. The wall can be steep in different heights and slope starting point to total wall height considered variety. The slopes can be placed under different angle to vertical axis. A main reason of considering a unit for length is great of the seawall to their section dimension. These structures are usually built along the coast. Thus, the behavior of a length unit can be representing entire wall behavior. The model is placing under radiation random waves for definite times. Time changes in the water surface profile, shear force and wall base moment are determined. Maximum values moments in each case are collected and compared to each other. In order to obtain the interaction between the wall and the waves used SACS software.

2.1 SACS software

SACS software is one of the strongest and most widely used software to design and analyze of maritime structures under various loading conditions. Figure 3 show subtypes of models generated and analysis by software under different conditions. In present study, seawall is under random wave loading. Therefore, analyze the wall will be kind of dynamic response analysis. The method dynamic response analysis is shown in Figure 4 (**Hooshyar**, 2009).

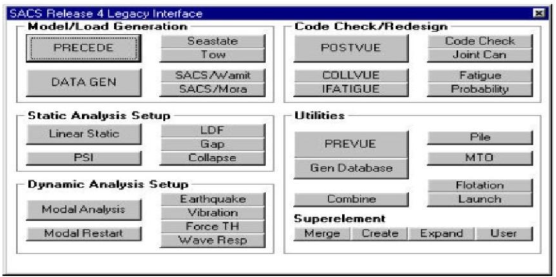

Figure 3: Entire structure of SACS software

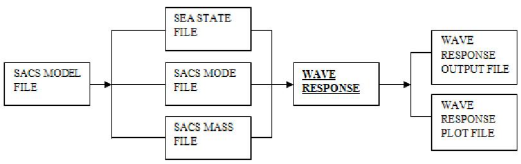

Figure 4: The method dynamic response analysis in SACS software [18].

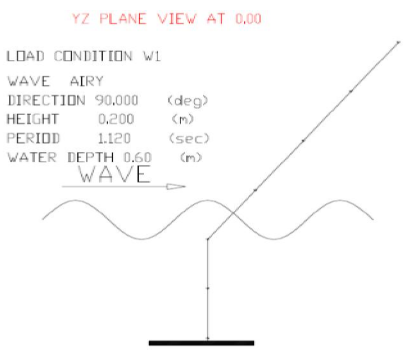

Figure 5: Seawall model in software

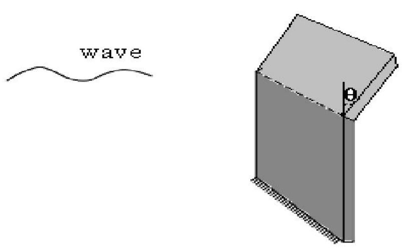

Figure 6: Three-dimensional view of the wall

2.2 Model used in software

Wall geometry model there is in SACINP subset. In this part in addition to introduce structural geometry, initial loading such as structure weight, static condition of the sea and the regular waves are introduced. This information will be use in dynamic response analysis. In figure (5) the model width section and in figure (6) wall three-dimension view is shown. In order to analysis of wave induced dynamic response first done linear static analysis then extract mode .To define irregular waves in software represented parameters of exerted waves due to environmental conditions. According to the model used in the present study the wave height 20 cm, water height 60 cm and JONSWAP wave spectrum ,γ parameter in 3/3 spectrum ,time of induced wave 300 seconds, parameter C in 0/142 spectrum and time pitch 0/02 seconds are applied. The wave period is usually 1 to 10 seconds at the practical works and period 2/5 seconds is suitable for condition of Iran beaches. Due to the similarity of Froude number and consider the scale of 1 to 5, the wave period 1/12 second is applied. Main reason of considering wave length 300 seconds and a time pitch of 0/02 seconds is appropriate overlap between JONSWAP spectrum and produced spectrum by the software.

2.3 Analysis done

To get the best steep slope and slope starting point in order to achieve a minimum flexural moment, seawall with dual slope is expressed in Figure 7.

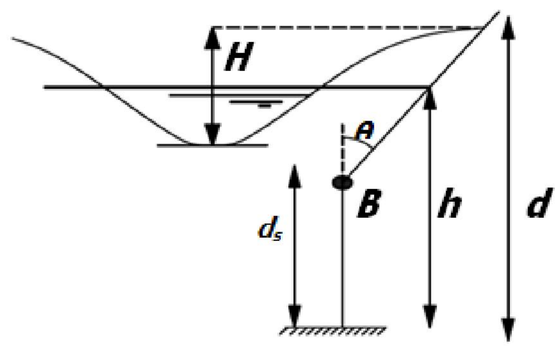

Figure 7: Manner placement compound steep wall against wave

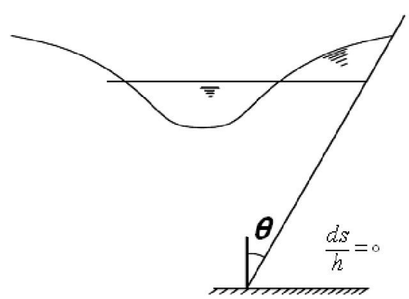

Figure 8: Full steep wall:

In this figure d_s is vertical height of the wall, d total wall height, h water height and θ is slope of wall. In vertical wall, θ=0 and in full steep wall d_s = 0. Range d_s from zero to 80 cm by changing 5 cm and placement angles values of wall steep part is considered between zeros to 45 degrees with a 5 degree change. For each case, static and dynamic and extract mode analysis done separately. Time history diagram of water surface, flexural moment and shear force, respectively have been achieved in figures 9, 10 and 11 during 300 seconds with pitch 0/02 sec. By comparing time history chart of the wall surface and the base flexural moment changes can be seen occurrence of the maximum moment does not compliance with peak water level linearity. Water level range and flexural moment are obtained in Figures 12 and 13, respectively. It is observed that the maximum frequency range of 1 Hz and a maximum frequency range of the flexural moment is 3/6 Hz. Due to obtained results of wall extract mode analysis, its fundamental frequency in the first mode was 3/61 Hz can be considered the dominant frequency in response of wall moment is the first wall mode frequency.

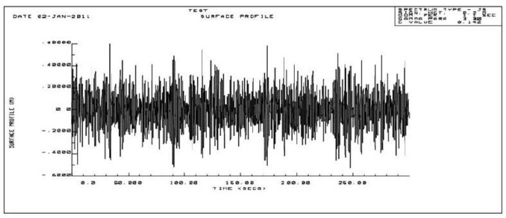

Figure 9: Water surface time history Graph

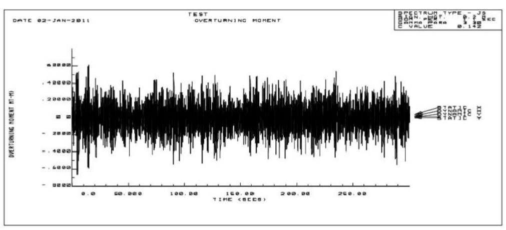

Figure 10: Wall flexural moment time history graph

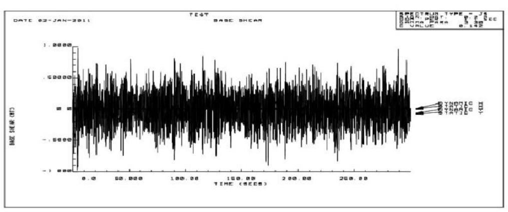

Figure 11: base shear force Time History Graph

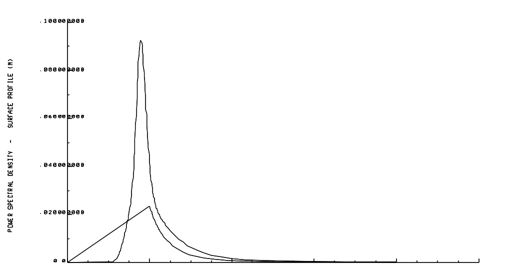

Figure 12: Water surface range

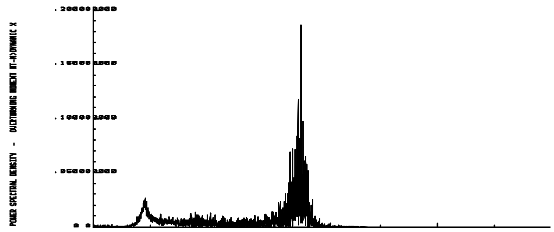

Figure 13: Base flexural moment range

3. Result and Discussion

With respect to the above issues in order to determine the start point and the most optimal slope from floor to 80 cm height in each 5 cm and different slope with angle pitches 15 degrees analyzed between zero and 45 degrees. In each time series maximum values of flexural moment are obtained during 300 second random wave radiation. Figure 14 shows results of the analysis, in this figure flexural moment at vertical axis is dimensionless (M_r=M/(ρgd^3) per unit length of wall also, slope starting point is dimensionless(d_{rs}=d_s/h) .As can be seen at three angles the slope was studied on the wall with different starting point per d_{rs}=0/83 had minimum moment. This number offer proper slope starting point at 10 cm below water surface. Due to water height is 60 cm and effective wave height is 20 cm, in present model obtained result show if slope starting point equals half effective height at water surface , induced flexural moment in wall base had least values. In figure 15 slope angles per d_{rs}=0/83 has been drawn ranging from zero limit to 45 degree with change 5 degree. Can be seen after angle 35 degree the moment remains constant. So in the model, slope starting point equal to half of wave height is lower than free surface of water below slope 35 degree to vertical slope. The final shape of the wall is plotted in Figure 16 in order to accurate represent.

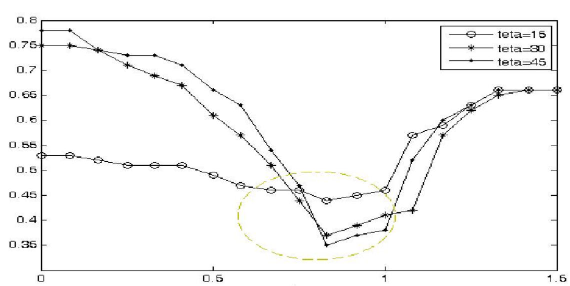

Figure 14: Graph of changes d_{rs} against M_r in angles 15, 30, 45 degrees.

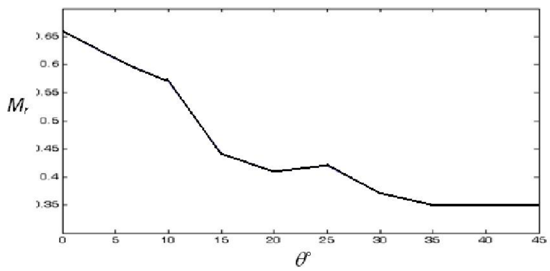

Figure 15: Graph of angle changes against M_r in angles zero to 45 degrees with changes 5 degree per d_{rs}=0/83

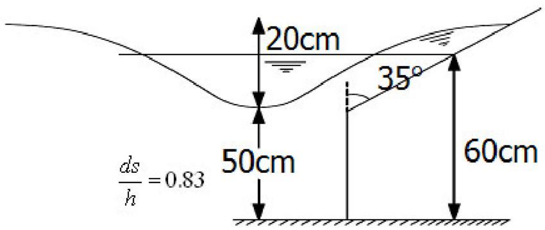

Figure 16: Manner placement wall against wave

4. Conclusions and suggestions

Based on the analysis done in this study, the main results are summarized as follows:

1 - Seawall with double slope encountering with sea random waves have better performance rather than walls vertical and steep walls in order to achieve minimal base flexural moment.

2 - The best slope starting point in seawall of the present study model has been conducted in half of the wave height which is lower than the water level.

3 –Flexural moment per angle 35 degrees on the slope is least and increase angle more than this value does not effect on reduce moment (Vafaiepour, et al., 2010; Ahand et al., 2010).

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