

Pushover Analysis of Sheet-Pile-Wall type Wharf with Relieving Platform Located at Different Heights

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Abstract: Relieving platforms are horizontal structural members used for lowering the earth pressure on retaining walls. These platforms are ubiquitously used in port structures - particularly Solid Berth types. Wharves are structures constructed parallel to shoreline and forms a critical component in loading & unloading of Cargos from ships. Any damage to the Wharves will have catastrophic repercussions on the overall operation of port facility. Earthquake being the formidable force, it is imperative that extra caution is exercised while designing the Wharf structure. The Wharf considered here consists of steel sheet piling used as diaphragm wall near the open seaside and driven cast-in-situ piles on the hinterland side, while common platform connects these two composite materials. This paper presents results for Pushover analysis which is performed for platforms located at different heights i.e., $0.4H$, $0.5H$, $0.6H$, $0.7H$ and $0.8H$, where H is the height measured from dredge level to top of wharf. Results showed that the optimum height for the platform is located at $0.7H$ from the dredge level.

Keywords: Pushover Analysis, Wharf, Seismic, Plastic Hinge, Capacity Spectrum

1.0 Introduction

Performance Based Seismic Design (PBSD) – a displacement-based procedure has gained momentum in the past two decades and will be the future of seismic design. In this procedure, the owner/structural engineer can choose the appropriate level of ground shaking and level of protection for the specified ground motion. Performance level can be broadly classified into three groups – Life Safety protection, Controlled & Repairable damage, and Minimal Damage, capturing real behavior at every stage of life cycle of the structure. In ‘Life safety protection’, structure must be stable after the seismic event; while in ‘Controlled and Repairable damage’, structure responds in a ductile fashion experiencing limited inelastic deformation; finally in ‘Minimal Damage’, Structure presents elastic response with minor

residual deformations. In addition to providing the basic objective of ‘loss of life’, PBSD proved to be a cost-effective solution for nonstructural components also. Soon, PBSD will supersede the traditional force-based design.

2.0 Wharf Details

Solid type Berth structure is a popular method of construction along the shoreline to safely harbor cargo ships. This method is relatively lighter in construction and offers flexibility in inspection. In this method, the fill is extended till the berth front. ‘Structure with a relieving platform’ type of solid berth is analyzed in this paper. When the height of berth front exceeds around 10m, the use of relieving platform is essential. With the platform arrangement, the earth pressure on berth front is reduced to a significant degree aiding in overall economy of the structure.

The proposed Wharf is 200m long located in the southern part of India under seismic zone classification III and soil type 2. The structure is constructed on dense sandy layer overlain by medium dense silty sand. Driven cast-in-situ pile methodology is adopted with cast-in-place procedure for superstructure.

3.0 Methodology

A 2D model is developed in SAP2000 software for all five heights of the platform. Earth pressure obtained on sheet pile wall is applied as linearly varying load in SAP2000. Also, to capture SSI effect non-linear springs at 1.0m intervals are added for both type of piles. Live loads and their respective combinations are not considered in this paper. Since the objective is to compare the behavior at different platform heights, only permanent loads are considered.

In the capacity spectrum context, the point at which the demand and capacity curve intersect is termed as the performance point. The demand plot is obtained using 5% damped elastic response spectrum, while the capacity is obtained by plotting base shear vs roof displacement. The performance point yields target displacement which helps in categorizing the structure into specific performance level. The performance point is extracted from the software and tabulated in table 2 below.

4.0 Earth Pressure on Sheet Pile

Figure 2 shows earth pressure diagram for sheet pile wall. As can be seen from the figure, the zero-pressure point starts just below the relieving platform. Set of equations will help us to find the depth of embedment and the maximum moment encountered.

The intensity of active earth pressure at depth L is given by:

$$\sigma_1' = K_a L Y' \tag{1}$$

where K_a = Rankine active pressure co-efficient = $\tan^2(45 - \Phi'/2)$

Y' = effective unit weight of soil = $Y_{sat} - Y_w$

Depth L_1 is given by the formula,

$$L_1 = \frac{\sigma_1'}{Y'(K_p - K_a)} \tag{2}$$

Where K_p = Rankine active pressure co-efficient = $\tan^2(45 + \Phi'/2)$

Depth L_2 is given by the formula,

$$L_2^4 + A_1 L_2^3 - A_2 L_2^2 - A_3 L_2 - A_4 = 0 \tag{3}$$

$$\text{Where } A_1 = \frac{\sigma_4'}{Y'(K_p - K_a)} \tag{4}$$

$$A_2 = \frac{8P}{Y'(K_p - K_a)} \tag{5}$$

$$A_3 = \frac{6P[2ZY'(K_p - K_a) + \sigma_4']}{Y'^2(K_p - K_a)^2} \tag{6}$$

$$A_4 = \frac{P[6Z\sigma_4' + 4P]}{Y'^2(K_p - K_a)^2} \tag{7}$$

$$\text{Where } \sigma_4' = Y'L K_p + Y'L_1(K_p - K_a) \tag{8}$$

$$Z = \frac{\Sigma M_E}{P} \tag{9}$$

Here, ΣM_E – Summation of moments about point E

P – Horizontal Force

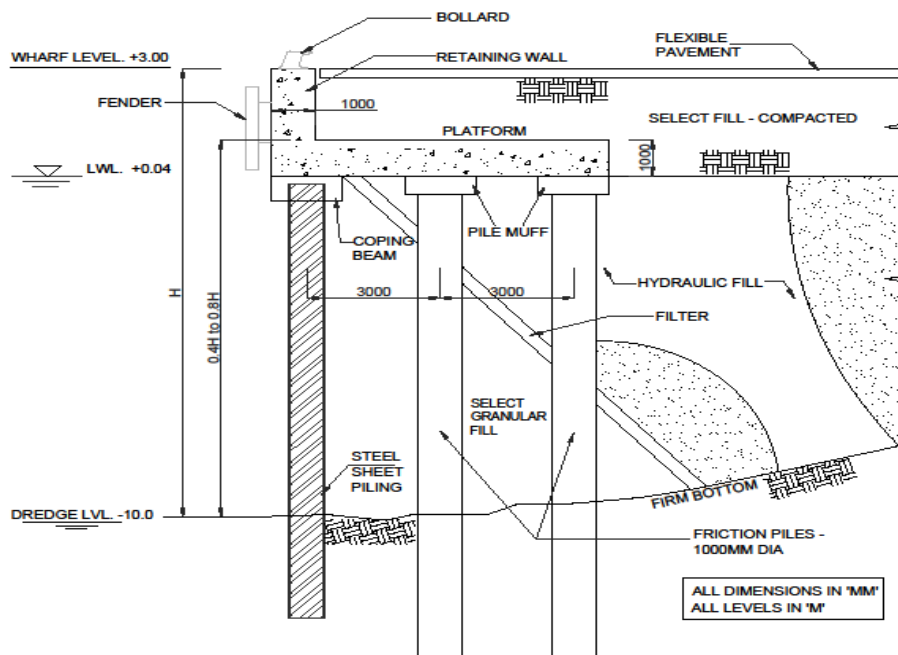


Figure – 1: Showing Dimensions & Levels of Wharf

4.1 Maximum Bending Moment on Sheet Pile

Maximum moment occurs at the point of zero shear. This point is located at z' from point E as shown in figure 2. The formula is given by:

$$Z = \sqrt{\frac{2P}{(Kp - Ka)Y'}} \quad (10)$$

The Magnitude of maximum moment is given by:

$$M_{max} = P(Z + Z') - [1/2Y'Z'^2 (Kp - Ka)](1/3)Z' \quad (11)$$

The required section modulus is given by:

$$S = \frac{M_{max}}{\sigma_{all}} \quad (12)$$

Where S = section modulus required per unit length of structure

σ_{all} = allowable flexural stress of the sheet pile

5.0 Earth Pressure on Retaining Wall

Coulomb's active earth pressure co-efficient is used for calculating pressure on retaining wall. In addition, live load surcharge effect is not taken into consideration. Figure 2b shows pressure diagram on retaining wall and same is applied in SAP2000 model.

Force due to earth pressure,

$$P' = 1/2 * \sigma_1 * h \quad (13)$$

Where $\sigma_1 = Ka.Y.h$

Here Ka = co-efficient of active earth pressure

$$Ka = \frac{\sin^2(\alpha + \Phi)\cos\delta}{\sin^2\alpha \sin(\alpha - \delta)} \times \left\{ 1 + \frac{1}{\sqrt{\frac{\sin(\Phi + \delta)\sin\Phi}{\sin(\alpha - \delta)\sin\alpha}}} \right\} \quad (14)$$

α = angle of wall w.r.t horizontal = 90deg

Φ = angle of internal friction of soil = 30deg

δ = angle of wall friction = 2/3 Φ

Y = dry density of soil = 20kN/m³

Here P' acts at 1/3h from base.

6.0 Depth & Spacing of Piles

The embedment depth below the dredged level is given by the formula:

$$L_e = 2L_f \quad (15)$$

Where L_f = Depth to fixity measured from dredged level

$$L_f = T \quad (16)$$

T is a stiffness factor and for Sandy soils is given by the expression:

$$T = (EI/\eta_h)^{1/5} \quad (17)$$

E & I are modulus of elasticity & Moment of Inertia of pile respectively in MN/m² & m⁴. η_h is the modulus of horizontal subgrade reaction in MN/m³. The spacing of piles is taken as three times the pile diameter for sandy strata.

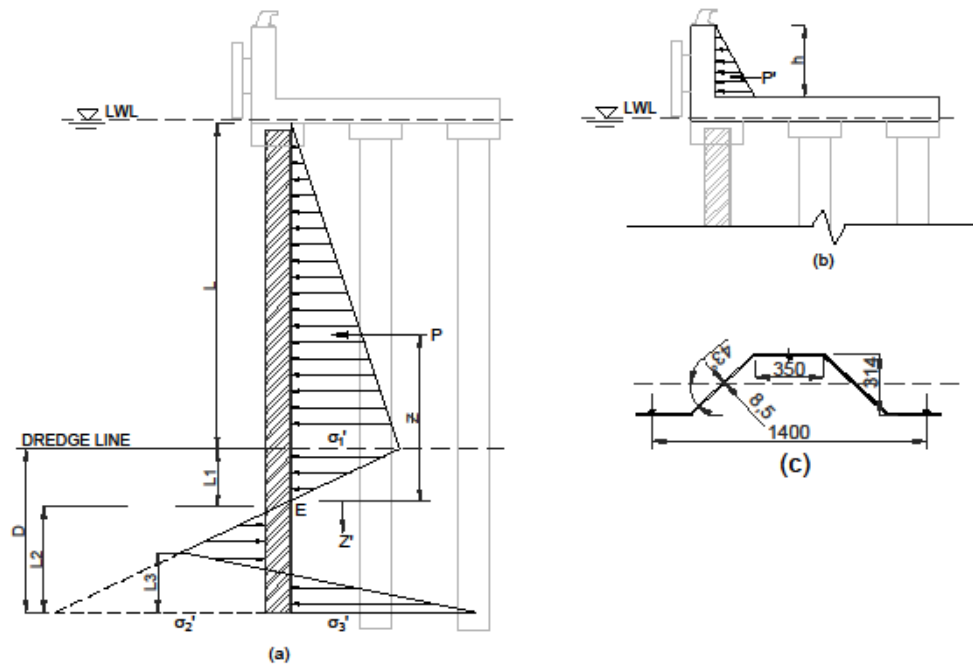


Figure - 2: Showing Earth pressure variation for (a) Sheet Pile wall (b) Retaining wall & (c) Section of Sheet pile

Table 1: Materials and Vessel used

Grade of Concrete	M30
Grade of Rebar	Fe500
Fender Type	Cylindrical rubber
Bollard Type	Steel T head
Vessel Type	Mixed Cargo Freighter
Sheet Piling	AZ 12-700, AZ 18-700, AZ 30-750

7.0 Pushover Analysis

Pushover analysis is a non-linear static procedure used to determine force-displacement relationship (Capacity curve) for a part or whole structure. The method involves applying horizontal loads until the collapse condition. The loads are applied incrementally and at each increment applied shear force and lateral displacements are recorded and plotted. Capacity Spectrum method of non-linear procedure is used in this paper. Both geometric and material non-linearity is considered in the analysis. Only column hinges are provided in the model since “strong deck-weak pile connection” philosophy is followed.

Fig 3(b) shows the locations of plastic hinges possibly developed in the structure. There are seven potential failure zones.

In order to convert traditional response spectrum curve to Acceleration-Displacement Response Spectra (ADRS), the following set of equations are to be used for Demand Spectra. To arrive at spectral acceleration S_a , multiply S_a/g by acceleration due to gravity ‘g’. To arrive at spectral displacement following equation is used:

$$S_d = S_a \cdot T^2 / 4\pi^2 \tag{18}$$

Here T is the time period

To convert pushover curve to ADRS format, following equation is used for ordinate:

$$S_{a1}/g = (V_1/W)/C_m \tag{19}$$

Where $C_m = M_1/M =$ mass factor

$W = Mg =$ total load

$V_1 =$ lateral base shear in first mode

The abscissa is represented by spectral displacement given by:

$$S_{d1} = \Delta_{max} / P_1 \cdot \Phi_{1max} \tag{20}$$

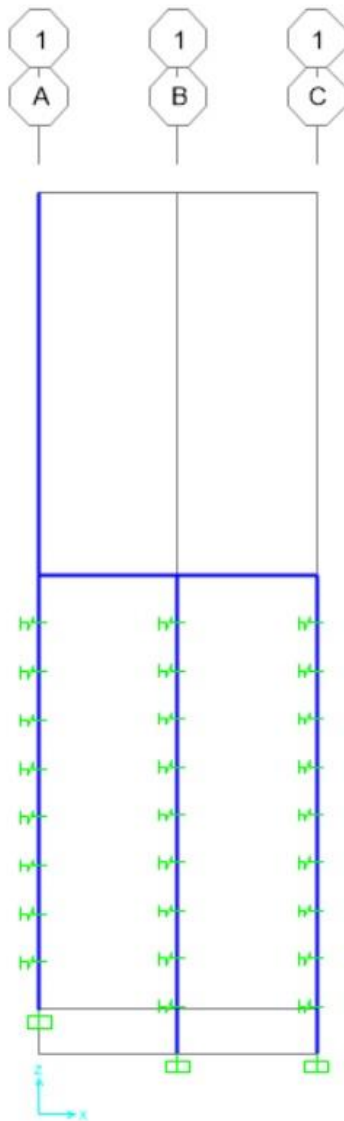


Figure – 3: Showing SAP 2D model

8.0 Soil Structure Interaction

During an earthquake event, the response of the soil which influences the motion of structure and the motion of the structure which in-turn influences the response of soil is termed as Soil-Structure-

Interaction (SSI). The influence of SSI enhances the effective damping ratio of the system - resulting in less seismic demand on the structure. Also, the structure is made more flexible with an increase in natural period of the structure.

To model springs in SAP2000, Beam on Winkler Foundation procedure is used for both RC piles and sheet piling to capture the effect of SSI (Indirect method). The non-linear P-y reaction springs are provided at every 1m interval along the length of the pile.

The subgrade modulus for sandy soils at depth z is given by:

$$Kz = n_h \cdot z \quad (21)$$

Where n_h = modulus of horizontal subgrade reaction (assumed as 4500kN/m³ for medium dense sand & 13000kN/m³ for Dense sand).

Spring value to be provided as input to software is given by:

$$k_{spring} = n_h \cdot B \cdot D \quad (22)$$

where B = Diameter of pile = 1.0m

D = Discretization of spring taken as 1.0m along the pile depth

Cumulative effect of spring values is taken into account. i.e. k_{spring} increases with depth of pile.

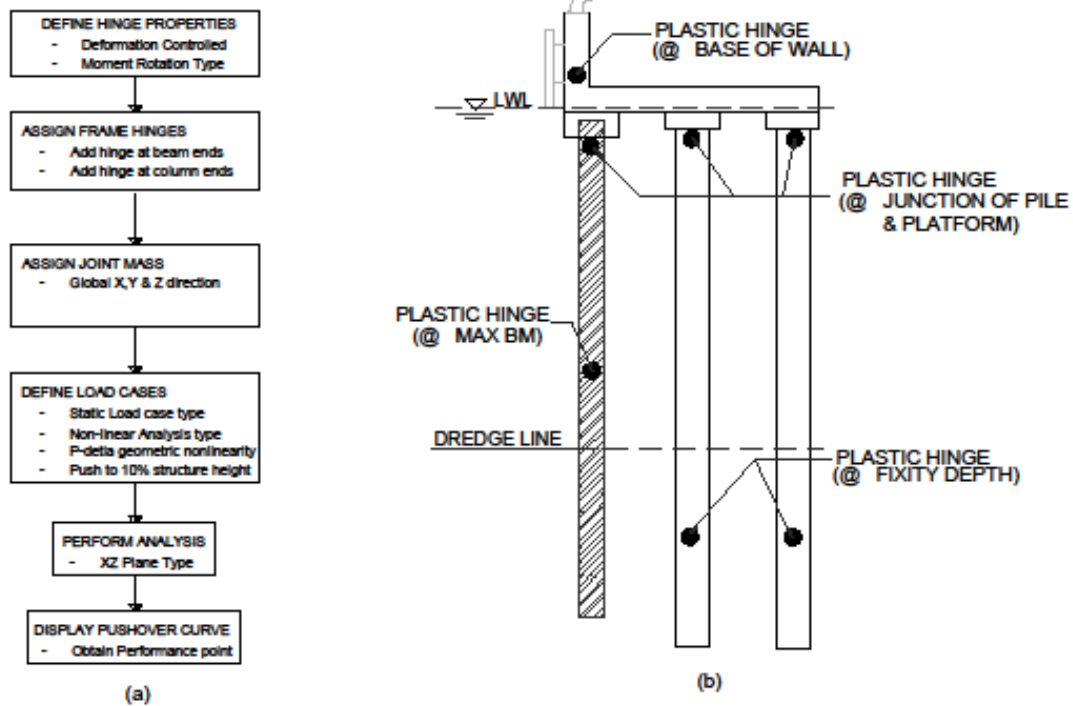
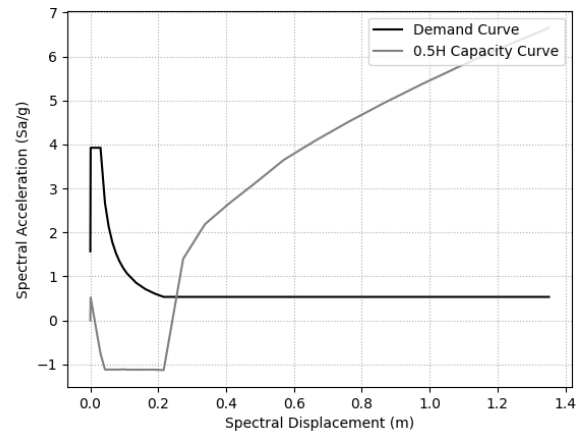
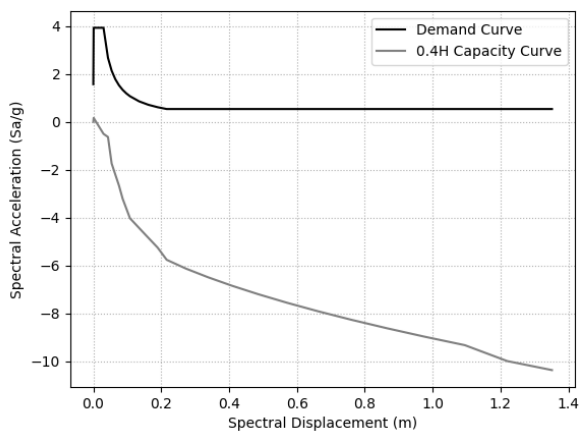


Figure – 4: (a) showing Pushover procedure in SAP2000 (b) showing plastic hinge as applied in SAP 2000



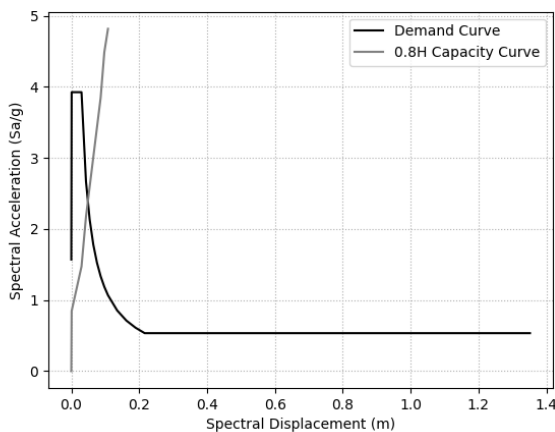
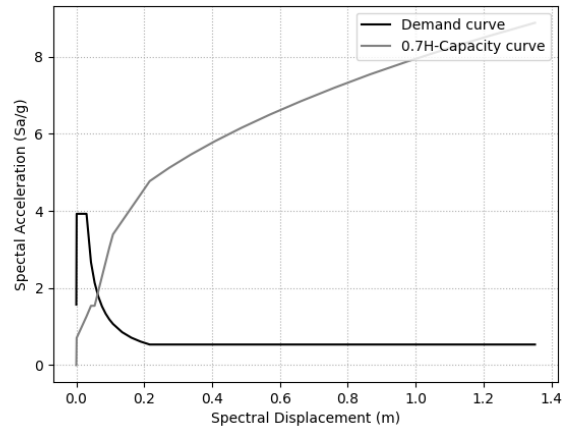
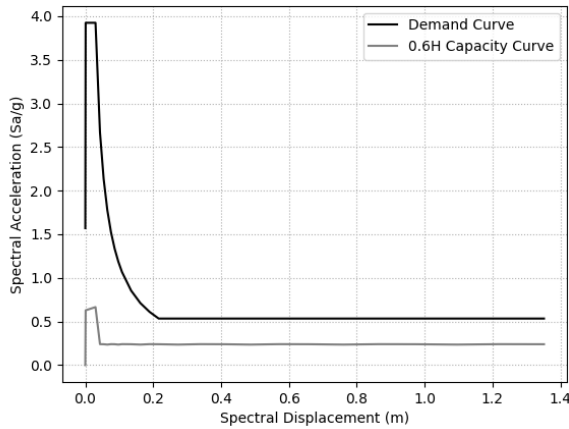


Figure - 5: showing Pushover curves for different platform heights

Table 2: Showing Performance Point

Location	Performance Point
0.4H	-
0.5H	(0.253, 0.560)
0.6H	-
0.7H	(0.062, 1.840)
0.8H	(0.049, 2.402)
wall	
Depth of Retaining wall (m)	7.80 6.50 5.20 3.90 2.60

Table 3: Summary of Forces

Location of platform	0.4H	0.5H	0.6H	0.7H	0.8H
Max Bending moment (kNm) on Sheet pile	35.69	86.9	172.8	302.1	483.7
Total Length of Sheet Pile (m)	8.644	11.0	13.14	15.102	17.060
Max Bending moment (kNm) on Retaining	645.4	397.1	221.4	106.1	39.0

9.0 Conclusions

1. From seismic perspective, it is recommended to position platform at 0.7H for best economy. As evident from the pushover curves, platforms at 0.4H, 0.5H & 0.6H will result in first plastic hinge formation at the junction of relieving platform and retaining wall. Hence the material will not be fully utilized.
2. Also from table 3, it is observed that the sum total of bending moments for Sheet pile wall & Retaining wall is minimum for 0.7H and also their respective depth required with an end result of economic design.

3. As seen from table 2, the displacement component is maximum for platform located at 0.5H. Hence requires maximum repair proving the most uneconomical height.
4. Again, from figure 4 for 0.4H height, constant stiffness degradation is observed, and the capacity curve fails to intersect the demand curve. Hence this arrangement is to be avoided at any circumstance.

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