Probability Concepts of Transfer Load to the Foundation of Container Structure

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Abstract: This paper presents stochastic analysis using the perturbation method to model the structure of a container to verify the distributions of probability of maximum and minimum axial forces reactions in piles. The proposed simulation of a container port terminal under 11 scenarios of load combinations was presented. The probability distributions for live loads are assigned according to the input parameters of simulation data. Part of the load itself is implicitly combined such as vertical live load which includes the weight of equipment and containers and wind load. The structural model was simulated in the software STAAD Pro., while the statistical analyses were performed with MATLAB. The results demonstrated that, the most significant external actions for the values of the axial forces reactions on the tips of the piles which considered appropriate to normal probability distributions.

Keywords: Probability, container foundation, stochastic analysis, perturbation method.

1. Introduction
With the technological development of the process of production and the increase of the world population occurred particularly in the last century, the requirement for products of the most varied categories increased considerably. This development is leading to the improvement of the techniques of shipbuilding, enabling larger ships, and containerization has made the port complexes become in supply sequences. Today almost all international trade and a considerable part of its domestic trade dependent on waterway transport as shown in Fig. 1. Structural systems in general are responsible for the stability of constructions, port structures, as well as, have additional importance, due to their functioning. Supply chains whose interruptions would result in huge costs to society. Chaining of containers, which allow the carrying out of operations loading and unloading. As for their structural kind, a structure can be classified as continuous or discrete. Due to the type of cargo that moves, has as its main peculiarity the actions arising from its equipment, specific for the transportation of cargo containerized.

Investigations of the behavior of the container foundation has often been studied by several researchers. In 2016, Vivek and Durga analyzed and designed marine berthing construction with several loading cases, they used information of Visakhapatnam Port to model the structure based on different scenarios of loading combinations. They studied members with variable section dimensions to satisfy all marine safety requirements [2]. In 2017, Kanakeswararao and Ganesh studied the behavior of pile under vertical and lateral load based on different approaches. P-Y curves and Vesic’s methods are used for calculation of vertical load in pile. They used linear elements to model pile and assumed Winkler soil spring in both horizontal and vertical directions. They calculated modulus of soil based on code 2911 and depended on Brom’s method to compare the results [3].
In 2018, Ćosić et al. presented a method to evaluate soil-pile-bridge pier interaction under seismic state. Nonlinear dynamic analysis was used individually for the analysis of pile and pier. The fragility curves were made depending on the probability theory of log-normal distribution and regression considerations. They used a difference of seismic state in a relation of scale for the intensity measure parameter, or Pin Grid Array according to the incremental nonlinear dynamic analysis [4]. In 2019, Su et al. used seismic fragility curves to assess large-scale pile in wharf with soil pile interaction. They found that soil pile interaction has a considerable effect on the behavior under seismic state. Piles that are supporting Port of Los Angeles Berth 100, USA have been studied with or without taking into consideration soil pile interaction. They concluded that a reliable estimation of seismic fragility in wharf structures is so important so that soil pile interaction can be either higher or lesser than the one without this consideration [5]. Other studies were investigated such as in references [6 and 7].

The current study is an attempt to present the uncertainty of reactions in the pile foundation of a container terminal under several scenarios of loading combinations. The next section describes the structure analyzed in this study.

2. Description of The Structure
The structure is a segment of a container port of a length of 42 m and a width of 20 m. It is supported by 60 piles. 24 of these piles are inclined in both directions to achieve resistance against lateral loads. The dead load in this structure is self-weight with a superimposed dead load. Four live loads are considered to be applied to this structure. Figure 2 shows a diagram of the structure with the loads. The first live load (LL1) is two vertical line loads on the rails which represent equipment, container, and wind loading. The second (LL2) and third loading (LL3) are ship collision scenarios at different locations. The fourth live load (LL4) is the pressure of the sheet pile adjacent to the structure.

The live loads are assumed to uncertain nature, so it requires stochastic analysis to get the variability of piles of axial forces with different load combination scenarios. The next section describes the methodology of the analysis used in this paper.

3. Methodology
Stochastic finite element analysis was conducted using the perturbation method. This method is based on calculating the response from each realization of input forces. Then the response from all realizations is collected to get the statistics including minimum and maximum piles of axial forces. In this study stochastic analysis with million realizations was conducted. By applying the superposition method of linear systems, finite element analysis using STAAD Pro. needed only to be done by applying unit loads at the location of live loads instead of repeating the analysis one million times. Then response from these unit loads are multiplied by live loads magnitudes to get real responses. The process is summarized in Fig. 3.
Figure 2. Schematic diagram of the structure with live loads.

Figure 3. The method of calculation of stochastic linear response by superposition method.
4. Finite Element Model
The structure beams and piles are modeled using beam elements, while the slab is modeled using plate elements. Piles tip are assumed to hinge. The slab dimensions are $20 \times 42$ m with a depth of 0.225 m. The beams heights are 0.625 m and widths are 0.7 m width. Piles section is tubes with an outer diameter of 0.7 m and a thickness of 0.15 m. The number of piles is 60 and the length of vertical piles is 20 m. The above dimensions are arbitrary and chosen based on British standards [8-11]. The material for the structure is concrete with a modulus of elasticity of 21.7 GPa and a density of 23.5 kN/m$^3$. Fig. 4 shows the analytical model and rendered view of STAAD Pro model.

![Analytical model](image1.png) ![Rendered view](image2.png)

**Figure 4.** STAAD Pro finite element model.

Some of the piles are inclined in both directions to achieve lateral loading resistance which can be seen in the front and lateral view of the analytical model in Fig. 5.

![Front view](image3.png) ![Lateral view](image4.png)

**Figure 5.** Front and lateral views of the analytical model.
Dead load is assumed to be self-weight combined with a uniformly distributed superimposed dead load of 5.3 kN/m² exposed to the slab. Four-unit loads are applied at live loads locations. The locations of the loads are the two uniformly distributed vertical loads representing the combined effect of equipment, containers, and wind at central longitudinal beams for load 1, lateral concentrated force near the corner at the edge facing the water for load 2 which represents ship collision, lateral concentrated force at the center of that edge for load 3 that represent ship collision at a different location, and lateral uniform distributed load represents sheet pile pressure. The loads locations in analytical models are shown in Fig. 6.

**Figure 6.** Live loads locations.
5. **Live Loads Distributions and Generation**

Live load values are assumed to be close to design values. Their distribution type and standard deviation are assumed to achieve uncertainty in their values. Table 1 shows live loads distribution types, mean and standard deviation.

| Load Case | Unit  | Distribution Type | Mean  | Standard Deviation |
|-----------|-------|-------------------|-------|--------------------|
| Live Load 1 | kN/m  | Weibull           | 80    | 15                 |
| Live Load 2 | kN    | Normal            | 3000  | 600                |
| Live Load 3 | kN    | Normal            | 3000  | 600                |
| Live Load 4 | kN/m  | Normal            | 150   | 15                 |

The distribution type used for loads 2, 3, and 4 is a normal distribution which probability density function (PDF) is expressed in the following relationship [12]:

\[
f(x) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{1}{2} \left(\frac{x-\mu}{\sigma}\right)^2\right)
\]

where \(\mu\) and \(\sigma\) are mean and standard deviation, respectively. Load 1 follows Weibull with the following PDF:

\[
f(x) = \left(\frac{k}{\lambda}\right) \left(\frac{x}{\lambda}\right)^{k-1} \exp\left(-\left(\frac{x}{\lambda}\right)^k\right)
\]

where \(\lambda\) and \(k\) are the distribution parameters. These above distributions can be generated from uniform random variables using the inverse transform technique:

\[X = F^{-1}(u)\]

where \(u\) is a realization of uniform random variable ranging from 0 to 1. \(F(x)\) is the cumulative density of function of the distribution to be generated which is related to PDF by:

\[F(x) = \int_{-\infty}^{x} f(x) \, dx\]

The mean for any random variable can be calculated from:

\[\mu = E(x) = \int_{-\infty}^{\infty} x \, f(x) \, dx\]

and variance:

\[\sigma^2 = \int_{-\infty}^{\infty} (x - \mu)^2 f(x) \, dx\]

where the standard deviation is the square root of variance. The generated loads of PDFs are illustrated in Fig. 7.

Using the method explained in Fig. 3, the response from each unit live loads are multiplied by their values in all one million realizations. Then, the responses are summed into combinations. All combinations scenarios for live loads are taken into account except those with live loads 2 and 3 together because both of them represent ship collisions at different locations. The self-weight and superimposed dead load are added to all combinations. The total number of load combinations is 11. After the load combination response values are calculated for all piles in the realizations, minimum and maximum axial load of the 60 piles is found for each load combination with each realization. The total number of minimum and maximum piles of axial forces is 11 million each, representing 11 minimum and 11 maximum axial forces for all the million realizations.
6. Stochastic Analysis Results

Figure 8 shows the PDFs of minimum axial forces (tension) of piles for selected important load cases. Table 2 gives the mean and standard deviation of those PDFs. It can be seen from the results that lateral loads are the most dangerous case in tension. The effect of the lateral impact of the ship at the center is less than that near the corner because the impact location is more distant to the inclined piles that absorb lateral forces. The combination of sheet pile pressure and ship collision has less effect than sheet pile alone because of the opposite force direction. Vertical load decreases the effect of other loading cases because it adds compressive forces to the piles. The case of only vertical load was excluded from these results because it increases the axial load in all piles.

| Load Combination | Mean (kN) | Standard Deviation (kN) |
|------------------|-----------|-------------------------|
| 2                | -726.535  | 243.743                 |
| 3                | -137.824  | 124.722                 |
| 4                | -828.762  | 131.236                 |
| 1+2              | -655.445  | 244.529                 |
| 1+3              | -66.334   | 125.67                  |
| 1+4              | -754.215  | 132.028                 |
| 2+4              | -739.802  | 131.637                 |
| 3+4              | -206.133  | 180.079                 |
| 1+2+4            | -669.509  | 133.083                 |
| 1+3+4            | -135.504  | 181.028                 |
Figure 8. Minimum axial forces in piles (Tension) probability density functions.

Figure 9 shows the PDFs of maximum axial forces (compression) of piles for selected important load cases. Table 3 gives the mean and standard deviation of the corresponding PDFs. Vertical loading combined with sheet pile pressure is the most dangerous case. Lateral loading of the ship collision when combined with that case will have a decreasing effect because of the opposite direction. Other load combinations of only lateral loads are not shown because they had a decreasing effect instead of increasing maximum axial loads of piles.

Figure 9. Maximum axial force in piles (Compression) probability density functions.
Table 3. Maximum axial force in piles (Compression).

| Load Combination | Mean (kN) | Standard Deviation (kN) |
|------------------|-----------|-------------------------|
| 1                | 1162.233  | 78.933                  |
| 1+2              | 1740.305  | 229.968                 |
| 1+3              | 1400.829  | 130.68                  |
| 1+4              | 2087.865  | 139.427                 |
| 1+2+4            | 1849.463  | 133.495                 |
| 1+3+4            | 1456.997  | 179.948                 |

7. Conclusions
This paper presented a stochastic analysis to model a structure of a container subject to uncertain loads using STAAD Pro and MATLAB. The study aimed to find the probability distributions of maximum and minimum axial forces in the piles. Eleven load combinations were used, representing dead load and four types of live loads. Live loads had uncertainty expressed by probability density functions. The results of minimum axial forces probabilities showed that lateral loads are the most dangerous in tension. The location of the ship collision had a significant effect on axial forces where collision on the corner has more effect than the center of the edge. Sheet pile loading also had a significant effect. However, combining the loading of sheet piles with ship collision or vertical loading had a reduction effect. The results of maximum axial forces showed that the combined effect of vertical loading with sheet pile pressure is the most dangerous case. That was reduced when combined with ship collision because of the opposite direction.

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