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Preface

These proceedings contain the papers presented at the TENTH INTERNATIONAL CONFERENCE ON ADVANCES IN STEEL STRUCTURES (ICASS 2020) held in Chengdu, China, from 21 to 23 August 2022. The international conference series on Advances in Steel Structures was initiated in 1996 under the support of The Hong Kong Polytechnic University, which remains very active in fostering its continuation—joined a few years later by the Hong Kong Institute of Steel Construction.

These proceedings bring together most recent findings in numerical, theoretical and experimental research, as well as its practical implementation in design practice in the areas of Assembled Structure, Bridge, Cold-formed Steel, Composite, Connections, Corrosion, Fracture & Collapse, Design & Analysis, Direct Analysis, Fatigue, Fire, High-Strength Steel, Impact and Protection, Intelligent Construction, New Material, Seismic Resistance, Stability, Stainless Steel, Structure Systems, Testing & Monitoring. The papers presented in these proceedings come from a wide range of countries/regions and will be a great reference source.

Specially, the subject matter has been categorized under the broad heading of:

**Volume I**: Keynotes Lectures, Assembled Structure, Bridge, Cold-Formed, Composite, Connections, Corrosion, Fracture & Collapse, Design & Analysis, Direct Analysis, Fatigue


Each of the papers was subjected to stringent review by a panel of experts in the respective area. This peer review began with an assessment of the submitted abstracts and following this, authors were invited to submit their full manuscripts. Each manuscript was then carefully reviewed by relevant experts, and their recommendations on accepting, rejecting or modifying the submissions were strictly adhered to, before inclusion in the conference proceedings.
Direct Analysis
SECOND-ORDER DIRECT ANALYSIS FOR STEEL H-PILES ACCOUNTING FOR POST-DRIVING RESIDUAL STRESSES

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Abstract: Driven steel H-piles are extensively adopted in engineering practice due to their convenience and efficiency in both economic and construction. The post-driving residual stress, a compressive axial stress distributed along the pile induced by the pile installation, might significantly deteriorate the pile bearing capacity. Thus, a large enough factor of safety is adopted in the traditional analysis to cover the influence caused by the post-driving residual stress. However, it sometimes leads to a large waste in costs and materials. Thus, the present study adopted the second-order analysis, a modern simulation-based design method, for the design of the driven steel H-pile. A robust and efficient finite element formula is necessary to conduct the second-order design method in practice. Hence, a new Line-Finite Element (LFE) formula is proposed in this paper. The developed LFE directly captures all the crucial factors in the analysis of the driven steel H-pile, including the nonlinear Soil-Structure Interaction (SSI) and the post-driving residual stress. A validation example is presented at the end of this paper, which illustrates the accuracy and the computational efficiency of the proposed LFE formula.

Keywords: Driven H-pile; Buckling; Soil-structure interactions; Post driving residual stress; Second-order analysis; Direct analysis

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1 INTRODUCTION

Steel H-pile is popularly used in congregated urban regions for its unique features in terms of fast construction and high in compressive capacity resulting from its large surface contact area with the ground medium for inducing high shaft frictions. Steel H-piles can be directly driven into the ground by movable pile-jacking machines [1, 2], whereas significant post-driving stresses might be induced to impair the pile load-bearing capacity [3]. Post-driving driving stresses (as illustrated in Figure 1) are compressive forces resulting from the elastic rebound of the pile after pile driving together with the recovery of the ground medium after the disturbance of the installation [4]. These stresses are self-balanced over the depth of pile in the absence of applied loads, which is small in the soft ground mediums, i.e. soft clay, but sometimes large in sands or other stiff ground mediums [5]. Post-driving residual stresses affect the steel H-pile behaviors in terms of load-bearing capacity and buckling strength significantly as revealed by a number of researchers, such as Cooke [6], Poulos [7], Fellenius and Altaee [8], Zhang and Wang [9] and so on. Against the background, this research focuses on the post-driving residual stresses modelling method for the analysis of steel H-piles in layered sands.

During the past four decades, several experiments have been conducted to investigate the residual stresses acting on steel H-piles. Costa et al. [10] undertook the laboratory tests on the piles buried in sands and measured the residual stresses, finding that the movement and the subsequent load in the pile are apparently affected by the residual stresses. Cooke [6] studied
the jacked steel piles in London stiff clay, and observed the significant influence of the residual stresses on the behavior of the jacked piles. Rieke and Crowser [11] carried out a load-test program to measure shaft friction and end-bearing stresses of an instrumented pile, revealing the importance of considering residual stresses. Zhang et al. [12] executed a large-scale field-monitoring program to monitor the residual stresses in long-driven piles with the lengths ranging from 34.2m to 59.8m, and their research reveals the residual stresses can impair the pile compressive capacity up to 40%. Seo et al. [3] carried out the in situ tests for assessing the axial load response of a steel H-pile driven in multilayered soil and observed the apparent deduction in the pile shaft capacity due to the existence of post-driving residual stresses. Ganju et al. [13] adopted both static and dynamic load tests on steel piles driven into a gravelly-sand soil profile, observing that the cone penetration test method can overpredict the pile shaft resistance capacity by a factor of two because of ignoring the residual stresses.

These studies indicate that the residual stresses increase along with the pile length, which will significantly affect the pile structural behaviors in terms of load-bearing capacities and deformations. As such, the appropriate consideration of the post-driving residual stresses is crucial for the design of the steel driven H-piles. However, this is always difficult because the distribution of post-driving residual stresses is highly nonuniformed, as reported by several researchers, such as Rieke and Crowser [11] and Kim [14]. To simplify the consideration, current design methods adopt the factor of safety (FOS) to cater to the influence of the post-driving residual stresses. For example, the FOS is 2.0 and sometimes 3.0 in CoPF2017 [15] for the design of driven steel H-piles.

The design method using the FOS is simple and usually very conservative, which is based on the linear and empirical analysis method of being unable to consider the effects of the soil-structure interaction (SSI) accurately. The consideration of the SSI can be particularly important when designing a structure with explicit modelling of its pile foundations via the nonlinear analysis method. The post-driving residual stresses can be classified as one type of the SSI relationships, besides that, the other two SSI relationships, i.e. the lateral force versus deflection (p-y) [16, 17] and vertical friction versus displacement (t-z) relationships [18, 19] (as illustrated in Figure 2), should be included in the analysis.
Various numerical methods have been developed to model SSI responses, such as finite difference methods (FDMs) [20], boundary element methods (BEMs) [21] and finite element methods (FEMs) [22, 23]. Aiming to practical applications, this research adopts the efficient Line-Finite-Element (LFEM) analysis method [24], and further develops for the analysis of steel driven H-piles considering the SSI relationships, i.e. the post-driving residual stresses, $p-y$ and $t-z$ relationships. The first attempt of using the LFEM for solving the pile analysis problems has been accomplished by Liu et al. [25], who refine the element formulations for the stability design of laterally loaded pile by directly modelling the soil springs along the element length. Later, Li et al. [26] further developed the LFEM method for analyzing piles, also named the method as the pile element analysis method, simulating both the $p-y$ and $t-z$ relationships.

In the present study, the LFEM analysis method is rederived for simulating the post-driving residual stresses in the element formulations, which is suitable for analyzing the steel driven H-piles in sands or stiff ground mediums.

In this paper, the LFEM implementation is elaborated with details where the SSI relationships are considered directly in the element formulations. The total potential energy is formulated and the shape functions for describing the strain and stress fields of the elements are presented. The element tangent stiffness matrix is then derived and the secant relations for computing the resisting forces are generated. The numerical procedure is briefly illustrated. Finally, four groups of examples are given to validate the accuracy and efficiency of the proposed method for analyzing the driven steel H-piles in different soil conditions.

### 2 Assumptions

The assumptions that the derivative process of the LFEM followed are made in this study:

1. strains are small, but displacements and rotations can be moderately large;
2. shear and warping deformations are ignored;
3. loads are conservative;
4. the material of the pile is homogeneous and isotropic;
5. the Euler-Bernoulli assumption is valid.
3 LINE FINITE-ELEMENT METHOD

A variety of numerical approaches, such as using Discrete Spring Element method (DSEM) [27], have been developed for analysing pile foundations. Since the soil reaction force are reflected by soil springs (Figure 3a), a large number of beam elements and soil spring elements are ineluctably required to model a single pile. Thus, the DSEM method is inefficient to simulate the considerably nonlinear SSI responses, especially in the large-scale soil-structure project analysis. As shown in Figure 3b, the efficient LFEM analysis method is further developed for the analysis of steel driven H-piles considering the distribution of residual stresses in full-scale tests. The load-displacement relations are portrayed by $p-y$ and $t-z$ curves, considering the non-proportional relationship between the soil resistance and displacement. Unlike the DSEM, the proposed method considers SSI responses by a group of nonlinear springs continuously integrated into the element (Figure 3b). The properties of soil springs are included in the element formulation, where fewer elements are used to simulate both steel driven H-piles and layered sands. Therefore, the proposed method not only brings convenience and efficiency in the analysis procedure, but also eases the difficulties of modelling layered sands, which is effective to major engineering projects with hundreds of driven steel H-piles for saving plenty of solution effort.

(a) Discrete spring element method (DSEM)
(b) The proposed Line-Finite-Element Method (LFEM)

Figure 3: Numerical analysis models for simulating the pile-soil system

The force-displacement relations of the efficient LFEM are plotted in Figure 4. The axial and lateral element shape functions can be written in the following matrix form:

\[
\begin{bmatrix}
u(x)
p(x)
\end{bmatrix} =
\begin{bmatrix}
\beta_1 & 0 & 0 & \beta_2 & 0 & 0 \\
0 & \beta_3 & \beta_4 & 0 & \beta_5 & \beta_6 \\
\end{bmatrix}
\begin{bmatrix}
u_1 \\
n_1 \\
u_2 \\
n_2 \\
\theta_1 \\
\theta_2 \\
\end{bmatrix}
\]

(1)

where $u(x)$ and $v(x)$ are the axial and lateral displacement functions, respectively; $u$, $v$ and $\theta$ represent the axial displacement, lateral displacement and rotation, respectively; subscripts 1 and 2 denote element ends; and

\begin{align}
\beta_1 &= 1 - \alpha \\
\beta_2 &= \alpha
\end{align}

(2)

(3)
\[
\beta_3 = 1 - \alpha^2 + 2\alpha^3 \quad (4)
\]
\[
\beta_4 = L(\alpha - 2\alpha^2 - \alpha^3) \quad (5)
\]
\[
\beta_5 = 3\alpha^2 - 2\alpha^3 \quad (6)
\]
\[
\beta_6 = L(-\alpha^2 + \alpha^3) \quad (7)
\]

where
\[
\alpha = \frac{x}{L} \quad (8)
\]

3.1 Total potential energy

The first line of the title starts 30 pt below the top edge of the text area. The title must be centered and written in uppercase using bold Times New Roman font with size 14. If the title extends over several lines, these lines must be single-spaced.

The element tangent stiffness matrix and the secant relations can be formulated by the principle of stationary potential energy, which is necessary for the numerical incremental-iterative type of analysis. The total potential energy function is given by:

\[
\Pi = U_E + U_S + U_R \quad (9)
\]

where \(\Pi\) is the total potential energy; \(U_E\) denotes the energy consumed by element strains, which can be found in Liu et al. [25]; \(U_S\) is the distributed soil springs, respectively; and \(U_R\) is the potential energy consumed by the residual stresses.

The energy consumed by the distributed soil springs can be expressed as:

\[
U_S = U_{SP} + U_{St} \quad (10)
\]

where \(U_{SP}\) and \(U_{St}\) denote the energy consumed by the lateral and vertical soil springs, respectively; and

\[
U_{SP} = \int_0^L \int_0^\gamma p(v)dvdx \quad (11)
\]
\[
U_{St} = \int_0^L \int_0^\mu t(u)dudx \quad (12)
\]

in which \(p(v)\) and \(t(u)\) are the lateral soil resistance and vertical fiction at the corresponding direction. Furthermore, the Gauss-Legendre method is introduced to compute the potential energy and further written as:
\[ U_{sp} = \int_0^L \int_0^p k(v) dv dx \approx \frac{1}{2} \sum_{i=1}^{n} H_i k_p(v_i) v_i^2 \]  

where \( H_i \) is the weight factor of the \( i^{th} \) Gaussian point; \( n \) is the number of Gaussian points; \( k_p(v_i) \) is the tangential value of \( p-y \) curve at a specified lateral deflection; \( v_i \) is the lateral deflection of Gaussian points.

Similarly, the energy consumed by the vertical resistance from the medium surrounding can be given:

\[ U_s \approx \frac{1}{2} \sum_{i=1}^{n} H_i k(u_i) u_i^2 \]  

where \( k(u_i) \) is the tangential value of \( t-z \) curve at a specified axial deflection; \( u_i \) is the axial deflection of Gaussian point.

The potential energy consumed by the residual stresses \( U_R \), can be given as:

\[ U_R = \int_0^L q(x) u(x) dx \approx \sum_{i=1}^{n} H_i q(x_i) u(x_i) \]  

where \( q(x) \) is the distributed load at a specified location of the element; \( x_i \) is the location of Gaussian point.

The work done by the external load can be written as:

\[ W = F_{x1} u_1 + F_{x2} u_2 + M_1 \theta_1 + M_2 \theta_2 + F_{y1} v_1 + F_{y2} v_2 \]  

where \( F_{x1} \) and \( F_{x2} \) are the forces caused by element strain at the two ends as referred to [25]; \( M_1 \) and \( M_2 \) are the bending moments caused by element strain; \( F_{y1} \) and \( F_{y2} \) are the forces induced by soil pressure; \( M_{1S} \) and \( M_{2S} \) are the bending moments caused by soil pressure; \( F_{1R} \) and \( F_{2R} \) are the forces induced by residual stresses.

The friction forces acting on the element can be expressed as

\[ F_{x1S} = \int_0^L \left( 1 - \frac{x}{L} \right) f(x) dx = \int_0^L (1 - \Delta) f(\Delta L) L d\Delta \approx L \sum_{i=1}^{N} G_i f(x_i) \]  

3.2 Secant relations for calculation resisting force

The equilibrium condition can be obtained by the first variation of the potential energy function according to the minimum potential energy method, which are given by

\[ \frac{\partial \Pi}{\partial u_i} = 0 \]  

The force on the pile can be divided two parts, the force from the straining energy of the pile, and the force from the distributed load of soil resistance and external distributed load. The total resisting forces vector \( \{ F_T \} \) are given by the following equations:

\[ \{ F_T \} = \{ F_E \} + \{ F_S \} + \{ F_R \} \]  

where \( \{ F_E \} \) is the element internal forces vector that commonly meet in Euler-Bernoulli beam-column element [25]; \( \{ F_S \} \) is the soil spring forces vector; and, \( \{ F_R \} \) is the residual load vector, as shown below:

\[ \{ F_E \}^T = \begin{bmatrix} F_{x1E} & F_{y1E} & M_{1E} & F_{x2E} & F_{y2E} & M_{2E} \end{bmatrix} \]  

\[ \{ F_S \}^T = \begin{bmatrix} F_{x1S} & F_{y1S} & M_{1S} & F_{x2S} & F_{y2S} & M_{2S} \end{bmatrix} \]  

\[ \{ F_R \}^T = \begin{bmatrix} F_{x1R} & 0 & 0 & F_{x2R} & 0 & 0 \end{bmatrix} \]  

where \( F_{1E} \) and \( F_{2E} \) are the forces caused by element strain at the two ends as referred to [25]; \( M_{1E} \) and \( M_{2E} \) are the bending moments caused by element strain; \( F_{1S} \) and \( F_{2S} \) are the forces induced by soil pressure; \( M_{1S} \) and \( M_{2S} \) are the bending moments caused by soil pressure; \( F_{1R} \) and \( F_{2R} \) are the forces induced by residual stresses.

The friction forces acting on the element can be expressed as

\[ F_{x1S} = \int_0^L \left( 1 - \frac{x}{L} \right) f(x) dx = \int_0^L (1 - \Delta) f(\Delta L) L d\Delta \approx L \sum_{i=1}^{N} G_i f(x_i) \]
where the subscript $s$ is the force caused by the soil pressure. The bending moments and shear forces caused by the lateral soil pressure can be obtained by

$$M_{ls} = \int_0^L x \left( 1 - \frac{x}{L} \right)^2 P(x) \, dx \approx L \sum_{i=1}^n O_i \, p(x_i)$$  \hspace{1cm} (22)

$$M_{2s} = -\int_0^L \frac{x^2}{L} (L - x) P(x) \, dx \approx -L^2 \sum_{i=1}^n O_i \, p(x_i)$$  \hspace{1cm} (23)

$$F_{ls} = \int_0^L \left( \frac{3x}{L} + \frac{L - x}{L} \right) \left( 1 - \frac{x}{L} \right)^2 P(x) \, dx \approx L \sum_{i=1}^n J_i \, p(x_i)$$  \hspace{1cm} (24)

$$F_{2s} = -\int_0^L \left( \frac{x}{L} + \frac{3(L - x)}{L} \right) \left( \frac{L}{L} \right)^2 P(x) \, dx \approx -L \sum_{i=1}^n J_i \, p(x_i)$$  \hspace{1cm} (25)

where the corresponding coefficients are given in Li et al. [26].

The residual load vector can be given as:

$$F_{x1R} = \int_L \left( 1 - \frac{x}{L} \right) q(x) \, dx = \int_0^L \left( 1 - \delta \right) q \left( \delta L \right) L \, d\delta \approx L \sum_{i=1}^n G_0 \, q(x_i)$$  \hspace{1cm} (26)

$$F_{x2R} = \int_L \frac{x}{L} q(x) \, dx = \int_0^L \delta q \left( \delta L \right) L \, d\delta \approx L \sum_{i=1}^n G_0 \, q(x_i)$$  \hspace{1cm} (27)

where the subscript $R$ is the force caused by residual stresses.

### 3.3 Element tangent stiffness matrix

In order to predict incremental displacements due to the corresponding forces, the tangent stiffness matrix is calculated by the second variation of the total potential energy function as:

$$\delta \Pi = \frac{\partial^2 \Pi}{\partial u_i \partial u_j} \delta u_i \delta u_j$$  \hspace{1cm} (28)

By using the second variation of total potential energy function, tangent stiffness matrix can be given as:

$$[k] = [k]_L + [k]_G + [k]_S$$  \hspace{1cm} (29)

where $[k]$ is the tangent stiffness matrix of the whole element; $[k]_L$ is the linear stiffness matrix; $[k]_G$ is the geometric stiffness matrix; and $[k]_S$ is the stiffness matrix for considering the soil resistance. Readers can find the linear stiffness matrix and the geometric stiffness matrix in Liu et al. [25].

The soil stiffness matrix, $[k]_S$ can be written as:
3.4 Numerical procedure

To consider large deflections of a LFEM, the Updated Lagrangian (UL) description are introduced. Then, the proposed LFEM and the UL description are implemented within the Newton-Raphson incremental iterative algorithm to eliminate the accumulate error in the nonlinear analysis [28-30].

4 VERIFICATION EXAMPLE

In order to evaluate the performance of the proposed line-Finite-Element method for driven H-steel pile embedded in layered sands, a steel H-pile embedded in layered sand is presented in this example. The information of the pile and the sand around it is given in Figure 5. As aforementioned, the SSI of piles can be comprehensively considered via different load transfer curves and the residual stresses curve. In the present study, the field-tested residual stresses (Figure 6) along the pile in the sand is reported by Rieke and Crowser [11]. And the corresponding load transfer curves are calculated according to API [32] and plotted in Figure 7.

where the coefficients \( A_1 \) to \( A_3 \) and \( B_1 \) to \( B_{10} \) at the Gaussian points are given in Li et al. [26].
In the conventional DSEM, 100 beam-column plus 200 spring elements and 11 beam-column plus 20 spring elements are used, respectively. However, in the proposed model using the LFEM, only 11 elements with 12 nodes are constructed. The comparison displacement results of the case are given in Figure 8. Apart from that, the results of residual toe load calculated from different methods are also plotted in Figure 6, which is part of the reason for the error from DSEM as shown in Figure 5. It can be found from Figure 8 and Figure 6 that the result from the present study with 11 elements can well match with the results from 300 DSEM elements.
which means that the proposed method can robustly and accurately simulate the buckling behaviors of H-steel pile considering the residual stress. Moreover, it should be pointed out that the most time-consuming step in a finite element method is calculating $\Delta U$, which means that a larger number of elements will significantly increase the size of the stiffness matrix and lead to more computational resource consumption. Furthermore, ignoring the residual stresses will cause huge errors in the design, which might lead to the failure of the pile due to the result without considering the residual stresses is nonconservative. Thus, it is helpful to implement the LFEM for practical applications on the large structures with hundreds of piles and thousands of structural elements.

![Figure 9: Residual point load calculated from different methods](image)

5 CONCLUSIONS

Jacked or driven H piles are preferred in term of fast construction and high compressive capacity, but its design should be accurately and efficiently considered otherwise may cause tremendous damage. This paper implements the LFEM for the driven steel H-pile in layered sand. In the numerical framework, the total potential energy function considering the SSI relations and residual stress is expressed by Gauss-Legendre method and used for getting the tangential stiffness matrix and secant relations. For eliminating the error accumulating in the calculation, the stiffness matrix and secant relations are integrated into Newton-Raphson incremental-iterative process. To simulate the large deflection behaviour of steel H-piles, the UL method is employed to establish the equilibrium conditions by referring to the last-known configurations. Finally, an example is given to validate the accuracy and efficiency of the present study for pile-related calculations.

REFERENCES


These proceedings contain the papers at the TENTH INTERNATIONAL CONFERENCE ON ADVANCES IN STEEL STRUCTURES (ICASS 2020) held in Chengdu, China, from 21 to 23 August 2022. The international conference series on Advances in Steel Structures was initiated in 1996 under the support of The Hong Kong Polytechnic University, which remains very active in fostering its continuation - joined a few years later by the Hong Kong Institute of Steel Construction.

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