Journal of Advanced Research Design 124, Issue 1 (2025) 21-32

Penerbit Akademia Baru

Journal of Advanced Research Design

Journal homepage:
https://akademiabaru.com/submit/index.php/ard
ISSN: 2289-7984

Experimental Study on Mechanical Behaviour of Full-Scale High Security Fence Structure

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ARTICLE INFO

Article history:
Received 11 May 2024
Received in revised form 13 December 2024
Accepted 13 January 2025
Available online 31 January 2025

Keywords:
High security fence; mechanical behaviour; experimental; static

ABSTRACT

The focus of this research is on investigating the mechanical behaviour of full-scale high-security fence structures through an experimental evaluation under static loading conditions. A full-scale experiment using a 12-meter-lengths High Security Fence was conducted to explore key mechanical performance aspects aimed at enhancing the security and reliability of high-security fence structure. This experimental evaluation assesses the structural performance of the High Security Fence under static loading conditions, considering the characteristics of material properties and applying loads according to specific loading configurations until the fence structure experiences grand displacements, providing insights into deformation patterns, and identifying potential structural vulnerabilities. Key findings from this research include providing a comprehensive understanding of the structural response of high-security fence structures under static loading conditions, highlighting critical factors influencing their mechanical behaviour and performance. The integration of experimental data and property material test results bridges the gap between theoretical analysis and practical applications, enabling informed decision-making regarding material selection.

1. Introduction

High-security fences are built to protect assets or vital areas such as prisons, national borders, embassies, mining areas, industrial zones, factories, and military installations. These high-security fences, made of galvanized steel wire coated with rust-resistant material, have a narrow mesh density between the steel meshes, making it unclimbable, difficult to cut, and capable of deflecting bullets. The high security fence should have the ability to provide a substantial delay against determined attackers to break using equipment or tools and provide a high level of resistance against any attempt to climb, cut and burrow under. This experimental evaluation assesses the structural performance of the High Security Fence under static loading conditions, considering the characteristics of material properties and applying loads according to specific loading configurations until the fence structure experiences grand displacements, providing insights into deformation

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https://doi.org/10.37934/ard.124.1.2132

patterns, and identifying potential structural vulnerabilities. Performing a static load test involves applying a gradually increasing load to a structure or component to assess its response and behavior under load. Fence structures under static loading, highlighting critical factors influencing their performance and structural integrity. Objective of this test to optimize material selection, design, and structural resilience, crucial for enhancing security and reliability.

Static load-deflection curve from a structural element is used mainly to characterize its stiffness evolution and flexural capacity before failure. Previous studies have investigated the mechanical behaviour of various structural systems under static loading. For instance, Sharaf *et al.,* [1] has performed an experimental and numerical investigation of the mechanical behavior of full-scale wooden 123 KV 13 L Cross-arm that used in transmission towers. Two points bending test was conducted to obtain load-deflection data of both scenarios, normal condition scenario and broken wire condition scenario. Determination of properties of the full-scale structures will provide reliable data and identify failure behaviors critical to the structure.

Experimental investigation analysis of the load deformation response of PVC fencing structures was also conducted by Sotayo *et al.,* [2] describes an investigation of the load-deformation response of a two-bay PVC post and rail fencing structure. The fencing structure was loaded experimentally at the top of the center post and mid-bay points of the top rail. The load-deflection responses recorded during the tests on the fencing structure are presented and shown to be both linear and repeatable. This study evaluates and quantifies the transverse stiffness of a representative PVC fence, and therefore acts as a benchmark which may be useful for evaluating the structural design and analysis of future novel materials and components for fencing applications.

The static load test verifies foundation design parameters and installation method [3]. For this study, the foundation for the fence structure in this experiment is done by manual auger. Various experiments were conducted to know behavior of auger cast-in-place piles in multilayered soil [4-15]. In auger foundations, a several study about comparison of the load-bearing capacity of the pile base and shaft with different methods of applying the load was introduced. A small crack was modelled between the vertical and horizontal beam, allowing for the displacement of the horizontal beam [16,17]. There is also numerical analysis to determine the optimum distance of reaction piles in a static pile load test in various experiments that are taken from the previous study [18-20].

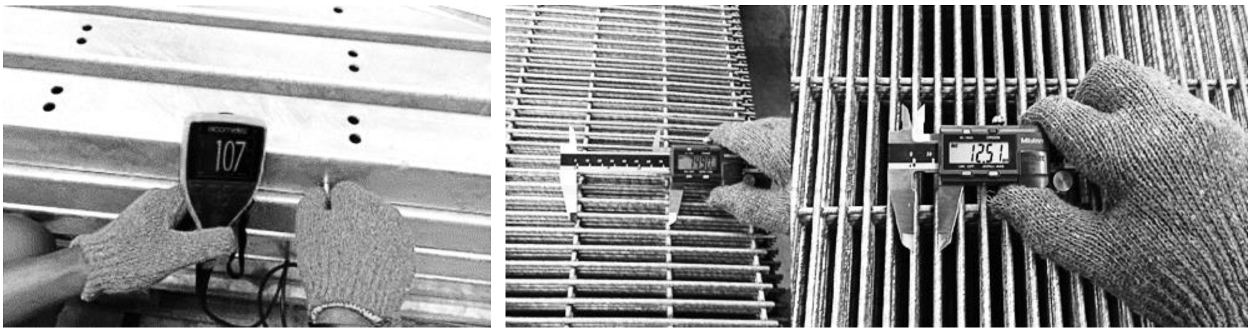
The mechanical behaviour of thin-walled structural components under combined mechanical and thermal loading conditions has been extensively studied Amran *et al.,* [21] providing insights into buckling patterns that can be analogously applied to high-security fence designs under complex loading environments. However, these investigations largely focus on structural components with different functional requirements and fail to address the unique demands of high-security fencing systems.

Despite the extensive body of research on structural performance under static loading, there is a notable lack of comprehensive studies focusing on high-security fences. These fences play a critical role in ensuring the safety and security of sensitive areas, yet their performance under static loads, particularly about stiffness, deformation, and failure mechanisms, remains underexplored. Bridging this gap is imperative to advancing knowledge in the field and improving the design and resilience of high-security fences to meet rigorous security demands. This study aims to experimentally investigate the static performance of high-security fences by analysing their load-deformation responses under controlled loading conditions. The research seeks to identify critical factors influencing structural integrity and optimize material selection, structural design, and resilience, thereby enhancing the reliability and effectiveness of these fences in real-world applications.

2. Methodology
2.1 Material Properties

The design and details of steel structures shall be in accordance with Specification for Structural Steel Buildings and, the 13th Edition AISC Steel Construction Manual and British Standard BS:1722 for Security Rating 2 (SR2) High Security Mesh Fencing. High security fence components (bottom rail, top rail, frame, support square pipe, bolt, nut, welded mesh panel) were supplied from West Java, Indonesia, and usually used for National Vital Object like prison, airport, or factory. A material specification sheet listing mechanical properties of high security fence was provided by the manufacturer. The mill's certificate from manufacturer were carried out for ensuring all materials already meet standards and codes. As a results the specification as follow with size panel dimension are (h x w): (2.4 x 3.0) m, steel wire diameter 4 mm, welded Mesh distance between horizontal wires shall be 75 mm, distance between vertical wires is 12.5 mm, the tensile strength ranged from 41-60 kgf/mm^2, shear strength minimum 20 kgf/mm^2 and for finishing material coated with Hot Dip Galvanized + mix 10% Aluminum or other additional protective coating based on ASTM A-123 with minimum galvanized is 60 microns. Steel shall comply with the requirements of ASTM A36, "Standard Specification for General Requirements Rolled, Structural Bars, Plates, Shapes and Sheet Piling". And for welding shall comply with the requirements of AWS D1.1. For fence accessories like bolts, nuts, and washers shall meet the requirements of ASTM A307. The galvanizing of all bolts, washers, nuts, and razor wire shall be done by the hot-dip process and shall meet the requirements of ASTM A123.

The minimum overall fence height is 3m including razor wire. Where razor wire continuous flat wrap type has a minimum tensile strength of 140 kgf/mm^2 with galvanized minimum weight 240 g/m^2, range of high tensile strength wire: 1400-1500 MPa, blade thickness: 0.5 ± 0.05 mm, core wire diameter: 2.5 ± 0.1 mm. Visual inspections were also carried out by QC Inspector with electrometer and Mitutoyo digimatic caliper for verifying and ensuring the materials meet all the requirements, codes, and standards. Inspection activities by QC inspector were conducted as shown in Figure 1(a) and Figure 1(b).



(a) (b)

Fig. 1. (a) Using electrometer to inspect the galvanized thickness (b) Using Mitutoyo digimatic caliper to dimensional check

As following to review manufacturer certificate, were found satisfactory; spot check/witness visual and dimensional check were found satisfactory; the visual in good condition, no found material damage during inspection. The dimensional and galvanized thickness, within tolerance. By conducted visual inspection it is evident that the mill's certificates testing is good within the manufacturer's range of values and based on specification material standards.

Left and right sides of the fence structure is supported by a square pipe in every 12 meters. For the foundation and tie beam of fence structure, this experiment use K400 or fc' 32.6 MPa. The foundation design is based on wind load 0.5 kN/m^2 and soil parameters. The type of foundation used is auger manual with depth 1.2 m and tie beam 40 cm with total 5 foundation points along 4 fence panels (3 x 4 m), with the structural fence of 12-meter length and supported with square pipe in span 12 meter, the deadload of fence structure (fence and foundation) is 2.8 Ton. With material fence Young modulus = E = 200000 MPa, and I = 27.7 cm^4, an assumption if there is a demonstrator or intruders (human) trying to push the fence in normally average height of Indonesian are 160-170 cm, and the maximum load occurred giving out by hands in height of 120 cm or 1.2 m (as a point load), then the load deflection to achieve 12cm (maximum deflection of the top of fence (2.4 m)) is 462 kg or 4.62 kN at 1.2 m from the bottom of fence.

2.2 Concrete Test Result

During the mock-up of the fence structure, the concrete cast-in-situ foundation and tie beam of auger manual cast-in-place final poured at 5th April 2024. The concrete samples were also made for concrete test. Compressive test for concrete were carried out by using compression machine digital with capacity 2000 kN. The environmental condition during the test was measured with temperature 25.4 ± 1.3^{o}C. Concrete compressive strength test was conducted when concrete age was reached 18 days (23rd April 2024), which is 3 days before static load test. Concrete test result as seen in Table 1. Below is a summary of the test.

Table 1
The values compressive strength of concrete K400 or fc’=32.6 MPa reached 18 days

No.	Sample code	Sample type	Weight (kg)	Cross-sectional area (cm^2)	Load (KN)	Slump (cm)	Compressive strength (MPa)	Percentage (%)
1	CT-HSF-1	Cyl 15x30	11.9	176.625	470	10	26.63	82
2	CT-HSF-2	Cyl 15x30	11.92	176.625	469	10	26.57	83
3	CT-HSF-3	Cyl 15x30	12.08	176.625	465	10	26.34	81

2.3 Test Instrumentation

Before horizontal load is given, several waterpass are used to ensure all the lifting gears are in the same steady elevation from the point load to anchor point. Waterpass needed along the process until the test ended. Waterpass is also used for ensuring the inclinometers are put in the right position.

For focusing on measured failure condition of the structure system and foundation, the instruments divide into 2 focusing parts. For measuring the deflection of fence material (line post, panel, and fence components) using digital theodolite as shown in Figure 2 for each fence post (4 points out of 5), divide to 3 points of survey (bottom, middle and top of fence). For measuring the deflection of foundation, 8 digital inclinometers have been employed to determine the deflection values due to the applied horizontal loads. As shown in Figure 3, 2 digital inclinometers were used perpendicularly in 4 foundation post. 4 digital inclinometers are divided to be installed on the X axis at each of the 4-foundation post and 4 digital inclinometers are on the Y axis on the 4-foundation post by placing in 20 cm depth to sense the deflection values. On the other hand, an electronic crane scale as shown in Figure 4 with capacity 10 Ton is used to measuring the applied load and gradually performing static horizontal load with pulling force from chain block.

Fig. 2. Total station for record deflection of fence line post

Fig. 3. Inclinometer for record deflection of foundation

Fig. 4. Electronic crane scale with capacity 10 Ton

2.4 Experimental Setting

Experimental full scale high security fence structure by static horizontal load test was performed in April 2024, located in Workshop Bekasi, West Java, Indonesia. The environmental condition during the test was measured with temperature 33°C. This experiment purpose is to know failure condition of the fence structure system and/or the foundation. The parameters to be measured are deflection of material fence structure (fence line post, panel, components) and foundation. Load tests were carried out on one point load in the middle span of high security fence structures along 12-meter length as shown in Figure 5.

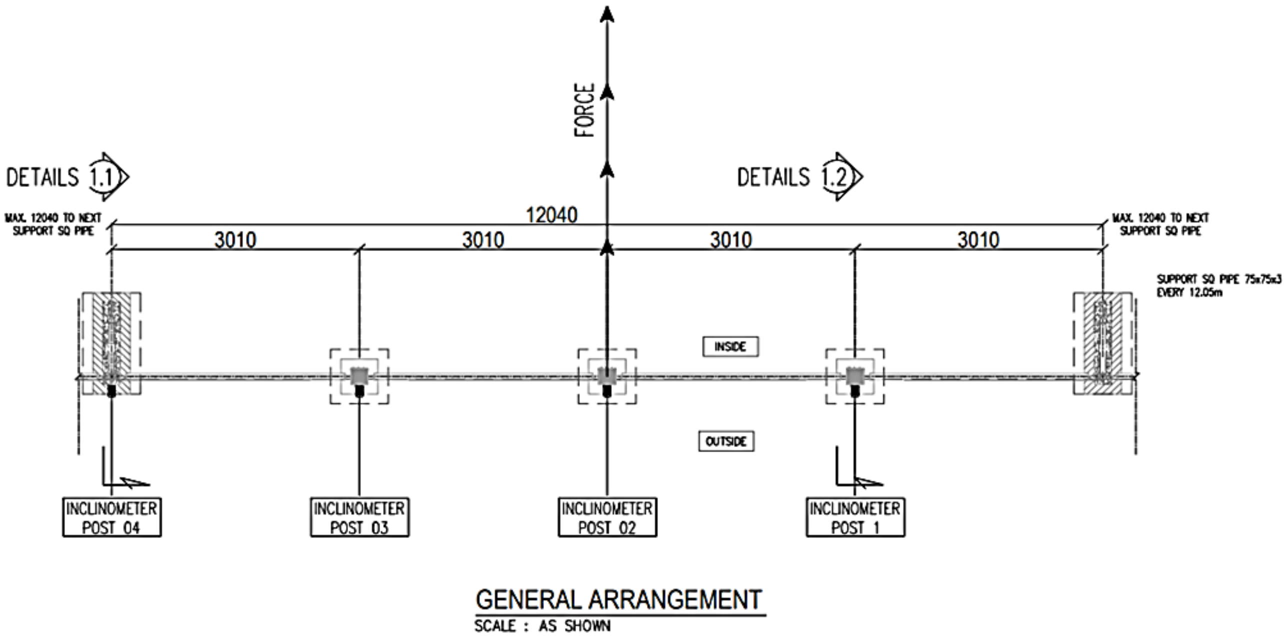


Fig. 5. Layout fence line post when static load test is conducted

In the design of fence structure, to achieve 12 cm maximum deflection on top of fence (2.4 m) needs 462 kg horizontal load based on cantilever calculation. For measuring material fence (line post) deflection, 3 survey point or mark testing point that already marked by a marker in fence line post (bottom, middle and top of fence) will be observed by total station or theodolite as shown in Figure 6.

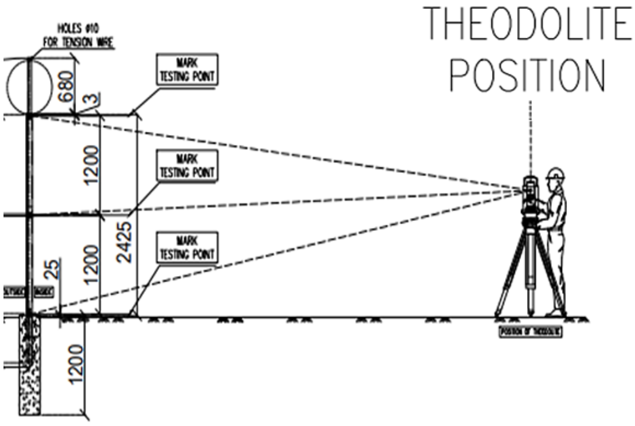


Fig. 6. Total station to survey 3-mark testing point

At the middle of the fence structure or line post number 2 which is 6 meters from the edges as a middle of the fence a lifting gear is attached to performed as a one-point load. For ensuring the same steady elevation by optimizing lateral force was carried out by installing the wire sling at fence line post number 2 as a pointed load structures then connecting wire sling with shackle and electronic crane scale, add chain block as a lifting device by hand power rate, and connecting the lifting gear with pin counterweight of forklift as an anchor point as shown as Figure 7. Make sure all the lifting gear in same steady position controlled by water pass. Equipment or lifting gear were used in this experiment are mentioned in Table 2.

During the horizontal static load test, the lifting gears as shown in Table 2 must be properly installed according to their functions, ensuring the safety and all measurement equipment can work properly to maximize data acquisition. Chain block was used to pull force and as a control to gain load electro crane scale is also employed. To maintain the stable elevation during horizontal static load test, forklift with capacity 10 Ton was added as an anchor point.

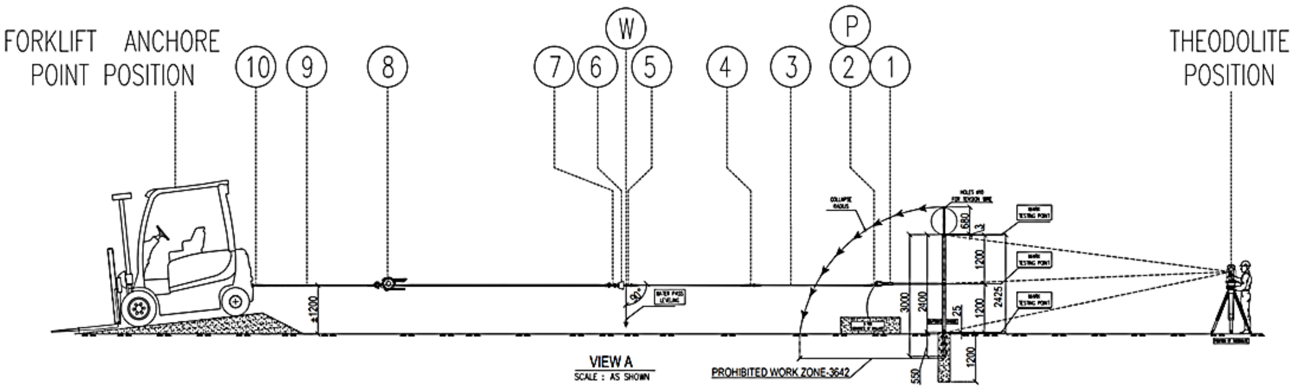


Fig. 7. Horizontal static load test high security fence

Table 2
List of lifting gears

ID	Item	Length (m)	Capacity (ton)	Weight /ea (Kg)
1	Wire sling	3	5	6.6
2	Shackle 1"	-	8.5	2.28
P	Sling protection	-	-	-
3	Wire sling	3	5	6.6
4	Shackle 1"	-	8.5	2.28
5	Wire sling	3	5	6.6
	Shackle 1"	-	8.5	2.28
W	Water pass levelling	-	-	-
6	Electro load crane	-	10	48
7	Shackle 1"	-	8.5	2.28
8	Chain Blbock	10	6	65.7
9	Wire sing	2	5	4.4
10	Shackle 1"	-	8.5	2.28
Total weight (Kg)				149.3

2.5 Static Load Tests

Experiment was started from lifting gears were not attached as shown in Figure 8. A surveyor with a laser total station will survey the test marking point in each post to make sure according to X, Y, and Z axis. Then, install lifting gears including chain block and electronic crane scale. Check and ensure the correct position without connecting to the line post or pole. Install leveling string. Install safety lashing. Turn on electro load cell and make sure it is in zero position. To avoid fence structure is starting to deflect because of lifting gears weight, put support as shown in Figure 9. Then, check all levels from the ground of rump to top of concrete. Barricade the entire test area.

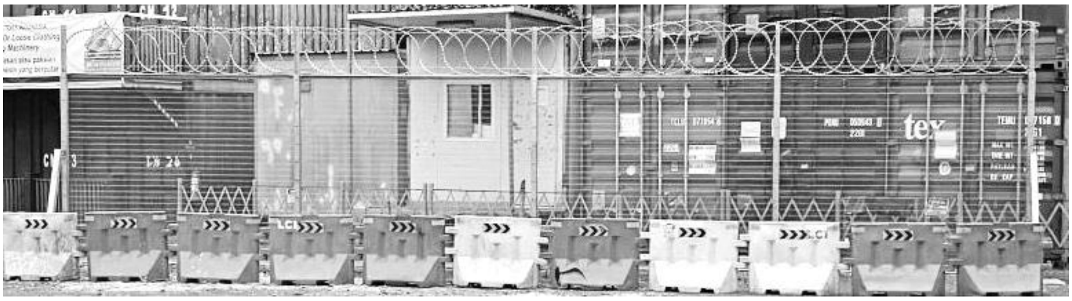


Fig. 8. Mock-up high security fence

Fig. 9. Support the lifting gear to avoid fence deflection before the experiment has started

The experiment including load scheme preparation by installing sling connection on the fence, measure deflection between the soil and the point of deflection drops, measure the actual height of the forklift anchorage point, measure the actual height of the sling to the ground (fence position). First, try with a small load gradually increased in every 5 minutes to observe the behavior. Check for changes in each pole for each load scheme change. All data will be recorded. Operator of electro crane scale, surveyor, operator inclinometer and chain block are synchronized together and pay attention to every aspect of measurement.

In each of 4 foundations post (out of 5), 2 inclinometers were placed perpendicular in foundation with the detail of 1 Y axis inclinometer was put into depth 20 cm from ground level (perpendicular to fence structure) and 1 X axis located on top of the foundation to measure and record horizontal deflections for each load increment as shown in Figure 10. Load tests on the fence ensured that the load-deflection response was linear elastic in the beginning. The horizontal static load test was applied for a specific time interval or until the rate of settlement falls to a specific value. In this experiment was repeated every 5 minutes until the structure cracked or failure. After fence structure has already failure and cracked, then gradually unload it. The fence structure may still provide resistance as part of the system. Recording data and measuring continues until unloading even if the material breaks, and the lifting gears are completely removed.

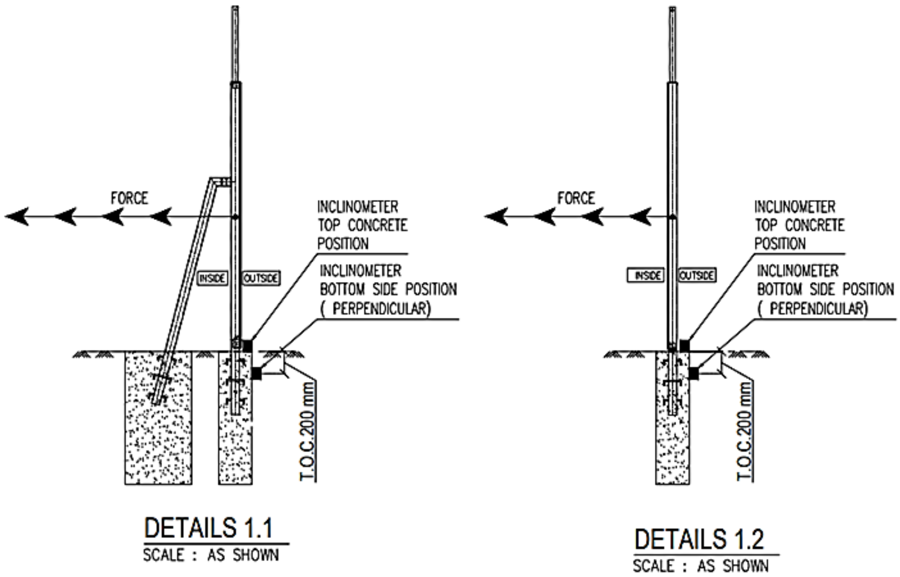


Fig. 10. Side view of static load test and position of inclinometers

3. Results

3.1 Fence Line Post or Fence Pole Deflection

This section discusses the results obtained from the static horizontal load test study from experimental mock-up high security fence. The test result of fence line post deflection for this experiment based on total station survey is presented in Figure 11. As shown in Figure 11, this static load test, focusing on deflection of fence line post or pole the load–displacement curve has been developed until reaching the maximum load of 15892.2 N and the maximum deformation of 775 mm was obtained in stage of peak load before failure. In the unload stage, 530 mm occurred then 514 mm has been recovered until the end of the test.

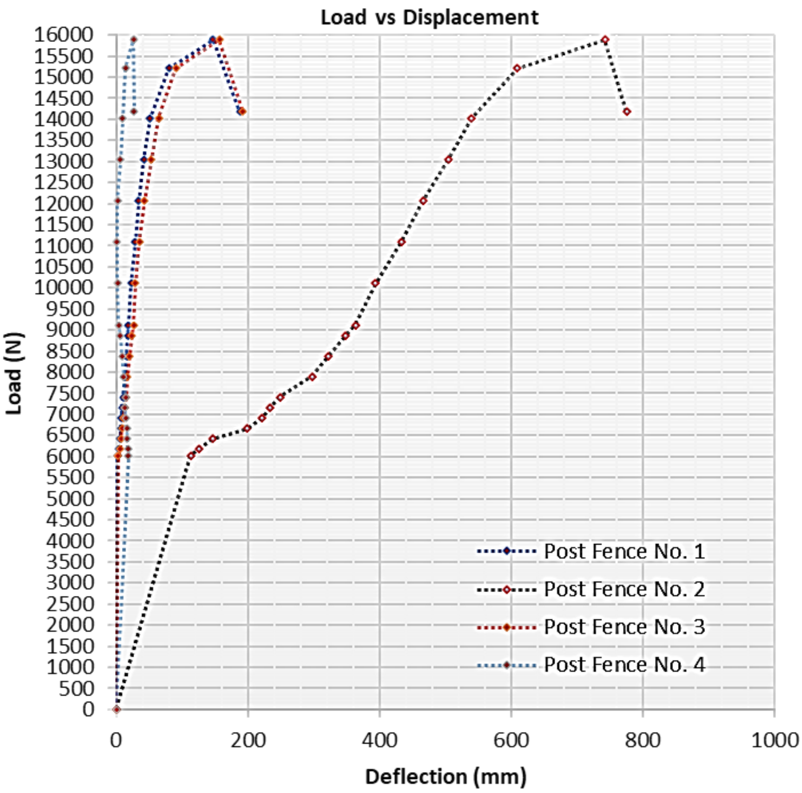


Fig. 11. Results of horizontal static load test

The maximum deflection is in line post number 2. It is occurred because the maximum and one point load located in this line post. But the other post shows the deflection occurred as well although as not as much line post number 2 as shown in Figure 12. Based on fence structure calculation and design, the failure of line post was predicted with maximum deflection 12cm at point load of P = 462 Kg which located at height of 120 cm or 1.2 m (as a point load). But the experiment shows the deflection at 12 cm gained at load of P = 432.5 Kg, which is less than the calculation design. Various factors trigger a reduction in the planned maximum load. Based on graphic, the fence could stand almost 3 times the design load, but the maximum deflection prediction from cantilever calculation occurred on 93% of design load.

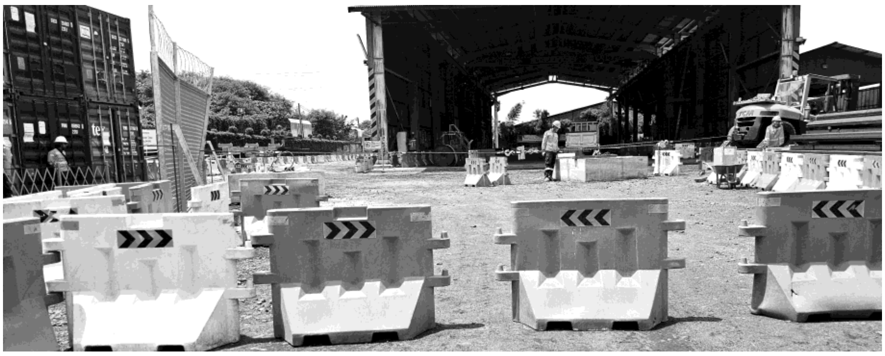


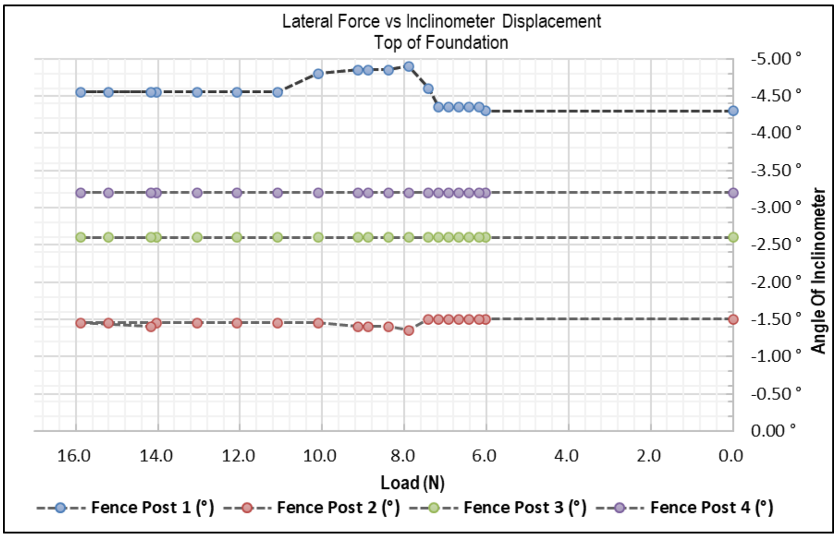
Fig. 12. Maximum deflection on post number 2

3.2 Auger Cast-In-Situ Foundation Deflection

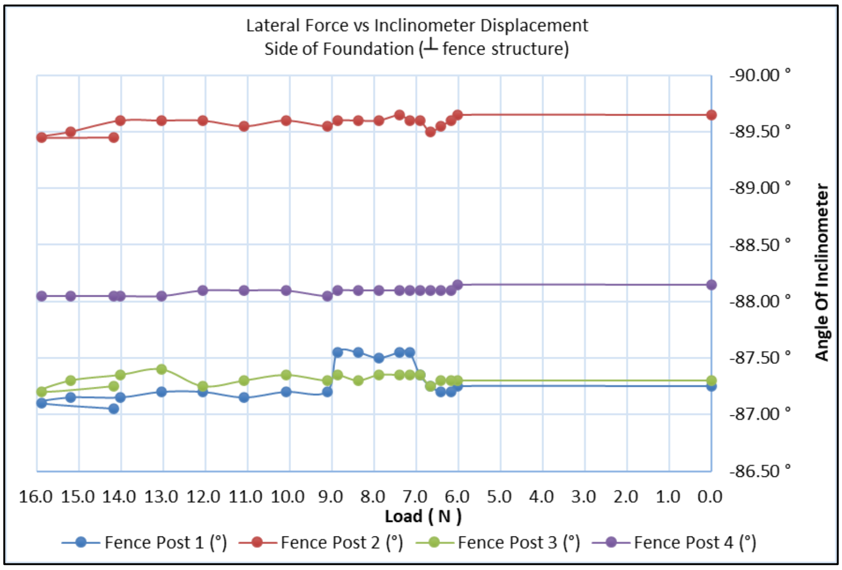
The test results of the Auger cast-in-situ foundation for this experiment, based on inclinometer readings, are presented in Figure 13(a) for the inclinometer located at the top of the foundation and

Figure 13(b) for the inclinometer located on the bottom side of the foundation (perpendicular to the fence structure) at a depth of 20 cm. Based on the results, measuring the inclinometer angle focuses on the deflection of the fence foundation, which is shown to occur up to the maximum load while still providing resistance as part of the system, even if the upper structure is already cracked and failing.

Based on Figure 11, it is interesting to note that the fence line post no. 2 already behaves inelastically at load 6000 N while the three other fence line posts are still in elastic condition. It is evident that the other line post and its wire mesh also contributed to the lateral strength of line post no 2. This condition is represented by the load deflection curve from all the line post after the peak load occurs, where their deflected shapes indicating permanent deformation. From Figure 13, at the same level of load and beyond, the passive pressure of the soil on the backside of the foundation has also significantly contributed to the resistance of the post no. 2 to face the horizontal static load. It is also represented by the permanent deformation of the soil on the backside of the foundation of the post no. 2, where angle of the inclinometer on both positions does not return to its initial value.



(a)



(b)

Fig. 13. (a) Results of inclinometer located at top of foundation (b) Results of inclinometer located at side of foundation

4. Conclusions

The experimental data of horizontal static load test during mock-up high security fence structure is presented here. Deflection values due to this load were determined by using laser total station for fence line post and 8 inclinometers for foundation that were installed. Based on the displacement result, in this static load test, focusing on deflection of fence line post or pole the load-displacement curve has been developed until reaching the maximum load of 15892.2 N and the maximum deformation of 775 mm was obtained in stage of peak load before failure. In the unload stage, 530 mm occurred then 514 mm has been recovered until the end of the test. It is concluded that the fence structure could stand almost 3 times the design load, and the maximum deflection occurred on 93% of design load. With measuring the inclinometer angle focuses on the deflection of the fence foundation, which is shown to occur up to the maximum load while still providing resistance as part of the system, even if the upper structure is already cracked and failing. As a system, high security fence structure lateral strength comes from both fence structure lateral strength and passive pressure of the soil on the backside of the foundation.

Moreover, this experiment needs further verification of the proposed numerical model requires simulation of other real tests in various ground conditions. Further study regarding numerical investigation non-linier analysis with software finite element analysis based on this experiment is needed to verify and validate the results.

Conflict of interest

The authors declare no conflicts of interest.

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