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The impact of dynamic loads on the displacement of drainage system during urban upgrading: A case study on Tran Van Hoai street, Can Tho City

Ảnh hưởng của tải trọng động đến chuyển vị của cống thoát nước trong quá trình nâng cấp đô thị: Trường hợp nghiên cứu tại đường Trần Văn Hoài, TP Cần Thơ

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ABSTRACT

This study examines the impact of dynamic loads on the displacement of drainage system along Tran Van Hoai Street, Can Tho City, using FLAC 7.0 simulations. The goal is to analyze the effects of dynamic loading on the culvert structure in the typical geological conditions of the Mekong Delta, which consist of alluvial soil, mud, and clay. The results show that dynamic loads significantly affect the displacement of the culvert, with displacements being 2.5 times greater than under static loads. Amplitude is the key factor, as larger amplitudes cause a noticeable increase in displacement, heightening the risk of damage and reducing drainage efficiency. Although frequency impacts displacement, the variation is minimal when the frequency ranges from 1 Hz to 5 Hz. The HL93 vehicle produces larger displacements than the Hamm 3412 roller, demonstrating that vehicles with greater loads and more intense oscillations cause more significant deformation. The findings highlight the need for detailed evaluation of dynamic load impacts during road upgrading projects, especially in areas with soft soil conditions like Can Tho City. To ensure safety and sustainability, measures such as soil reinforcement and optimized culvert design are recommended to improve urban infrastructure and support the city's long-term development.

Keywords: Dynamic load; displacement; drainage system.

TÓM TẮT

Nghiên cứu này đánh giá ảnh hưởng của tải trọng động đến chuyển vị của cống ngầm trong hệ thống thoát nước đô thị tại khu vực đường Trần Văn Hoài, TP Cần Thơ, thông qua mô phỏng số bằng phần mềm FLAC 7.0. Mục tiêu là phân tích tác động của tải trọng động đến kết cấu cống trong điều kiện địa chất đặc trưng của Đồng bằng sông Cửu Long, với lớp đất phù sa, bùn và đất sét. Kết quả nghiên cứu cho thấy tải trọng động tác động đáng kể đến chuyển vị của cống, với chuyển vị lớn hơn 2,5 lần so với tải trọng tĩnh. Biên độ của tải trọng động là yếu tố quan trọng nhất, vì biên độ lớn hơn sẽ làm tăng chuyển vị rõ rệt, làm tăng chuyển vị và từ đó có thể gây hư hỏng và giảm hiệu quả thoát nước. Mặc dù tần số có ảnh hưởng nhất định, nhưng sự thay đổi chuyển vị không lớn khi tần số thay đổi từ 1 Hz đến 5 Hz. Xe HL93 tạo ra chuyển vị lớn hơn xe Lu Hamm 3412, cho thấy rằng các xe có tải trọng lớn hơn và cơ chế dao động mạnh mẽ gây ra sự biến dạng lớn hơn cho cống. Kết quả nghiên cứu nhấn mạnh tầm quan trọng của việc đánh giá tác động của tải trọng động trong các dự án nâng cấp đường, đặc biệt là ở khu vực có nền đất yếu như TP Cần Thơ. Để đảm bảo an toàn và bền vững, cần áp dụng các biện pháp như gia cố nền đất và tối ưu hóa thiết kế cống ngầm, góp phần nâng cao chất lượng hạ tầng đô thị và hỗ trợ phát triển bền vững cho thành phố.

Từ khóa: Tải trọng động; chuyển vị; cống thoát nước.

1. INTRODUCTION

Urban expansion and population growth intensify pressure on underground drainage systems, where dynamic loads from traffic and construction accelerate structural deformation, especially in soft soils like the Mekong Delta. With rapid urbanization, underground space development has emerged as an optimal solution to maximize land use, alleviate surface infrastructure pressure, and enhance drainage efficiency. However, these structures face significant risks of subsidence and deformation under dynamic loading. Traffic-induced dynamic loads, combined with groundwater infiltration, can substantially increase structural displacement, particularly in urban areas with soft soils [1]. The study of [2]safeguard and the pipeline are considered as Euler Bernoulli's beam. Advanced soil model is used (viscoelastic foundation with shear interaction between springs utilized Plaxis 3D to evaluate the impact of vehicular loads on underground pipelines, revealing that as the applied load increased from 100 kN to 500 kN, pipeline deflection rose from 4.12mm to 17.54mm. This underscores the necessity of analyzing dynamic load effects on underground structures to propose appropriate reinforcement solutions. Previous studies have primarily focused on seismic or environmental loads, while the effects of vehicular and construction-induced dynamic loads remain underexplored. Dynamic loads can amplify structural oscillations by 3%-11% compared to static loads [3]. The study of [4] simulated pavement-induced vibrations, indicating that when vehicle oscillation frequencies range between 8-12 Hz, resonance may occur, increasing structural damage risks. In Vietnam, [5] applied Plaxis 2D to analyze underground structure displacement in soft soils, showing a maximum lateral displacement of 8.252×10^{-2} m, while vertical displacement was lower, reflecting the significant impact of dynamic loading. Study [6] simulated blast load effects on reinforced concrete structures in clay-rock environments using ABAQUS, highlighting stress variations between homogeneous and heterogeneous soil conditions. Although direct research on dynamic load effects on underground structures in Vietnam is limited, international studies confirm that dynamic loads tend to induce greater displacement than static loads.

Moreover, the study by [7] expanded upon and further clarified the findings of [8], indicating that the appropriate depth for placing underground culverts to minimize the impact of dynamic loads is around 700mm. Additionally, [9] also demonstrated that underground structures, when reinforced with surrounding materials, are less susceptible to the adverse effects caused by dynamic loads. The study [10] shows that the greater the depth, the smaller the displacement of the underground structure. These findings emphasize the need for in-depth investigations into dynamic load impacts on underground structures under real-world conditions in Vietnam.

In this study, a numerical simulation model using FLAC 7.0 will be applied to evaluate the displacement of underground drainage structures under static and dynamic loading. Various load types, including Concentrated Load (CL), Distributed Load (DistL), and Uniformly Distributed Load on the Wheel Track (UDLWT), will be considered to analyze the impact of dynamic loads at different frequencies (1 Hz, 3 Hz, 5 Hz). The findings of this study will provide a scientific basis for optimizing design and proposing maintenance solutions for underground drainage systems, particularly in soft soil regions such as Can Tho City.

2. METHODOLOGY

2.1. Study location

The study area is Tran Van Hoai Street, Can Tho City, as shown in Figure 1 and Figure 2. This area experiences high traffic density and is significantly affected by dynamic loads from vehicles, particularly heavy vehicles. The selection of this site aims to assess the impact of dynamic loading on underground drainage displacement in soft geological conditions, providing a basis for proposing technical solutions to enhance the durability and stability of urban drainage systems.

Figure 1. Tran Van Hoai Street, Can Tho City (Source: Google Maps)

Figure 2. Upgrading of Tran Van Hoai Street (Photo taken on February 24, 2025)

Figure 3 and Figure 4 illustrate the current and upgraded cross-sections of Trần Văn Hoài Street, Cần Thơ City, respectively.

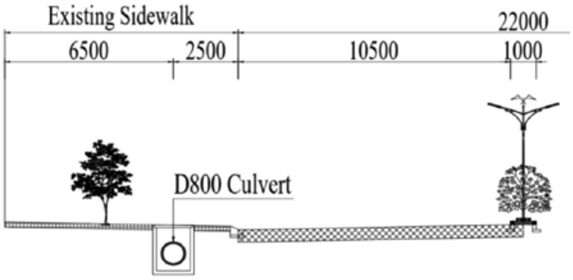


Figure 3. Half of the cross-section of the existing pavement (unit: mm)

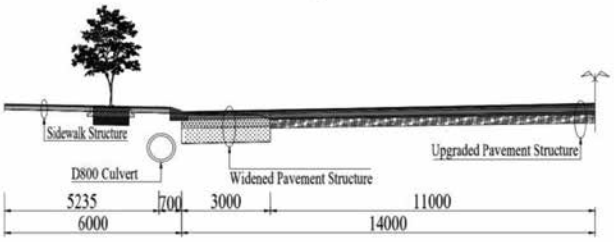


Figure 4. Half of the cross-section of the upgraded pavement (unit: mm)

2.2. Geological data

The physical and mechanical properties of soil are summarized in below.

Table 1. Geotechnical properties of the foundation soil

Soil Layer	Depth (m)	Unit weight (kN/m³)	Elastic Modulus (MPa)	Cohesion kN/m²)	Internal friction angle (°)
1	1,2	19,5	70.0	5	40
2	13,6	15,71	50	8.2	3.11

2.3. Pavement structure

The pavement structure layers are designed in accordance with the institutional standard TCCS 38:2022/TCĐBVN, "Flexible Pavement – Requirements and Design Guidelines.

Table 2 Simulation data for pavement structure

No.	Layer		Thickness (cm)	Unit weight γ (kN/m³)	Elastic Modulus E (MPa)	Poisson's ratio v
1	Side walk	MAC200 brick layer	5	22.0	24000	0.2
		sand backfill layer	20	19.5	70.0	0.3
2	Dense asphalt concrete c12.5		5	23.0	188.05	0.3
3	Medium-grained dense asphalt concrete C19		7	23.0	178.10	0.3
4	Grade I crushed stone base		15	21.0	155.20	0.3
5	leveling Layer of Grade I crushed stone base		5	21.0	155.20	0.3
6	existing pavement surface		30	23.0	188.05	0.3
7	Sand backfill layer		120	19.5	70.0	0.3
8	Subgrade soil		380	15.71	50.0	0.3
9	D800 Concrete pipe (MAC400)		10	24.5	32500	0.2
10	Pipe bedding		12	24.5	24000	0.2

2.4. Simulation case

This study evaluates the impact of vehicular loads on underground structures under different pavement conditions, including existing and upgraded roads. The two simulation vehicles include the HL93 vehicle and the Hamm 3412 roller, considered under static (SL) and dynamic (DynL) conditions at frequencies of 1 Hz, 3 Hz, and 5 Hz for the roller, and 0.1 Hz, 0.5 Hz, 1 Hz, 3 Hz, and 5 Hz for the HL93 vehecle.

Table 3. Simulation cases

Load type	Static load	Dynamic load									
		Frequency									
		0.1Hz		0.5Hz		1Hz		3Hz		5Hz	
		Amplitude									
		5%	10%	5%	10%	5%	10%	5%	10%	5%	10%
Hamm 3412	Case 1	-	-	-	-	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
HL93	Case 8	Case 9	Case 10	Case 11	Case 12	Case 13	Case 14	Case 15	Case 16	Case 17	Case 18

2.5. Dynamic model

Figure 5 presents the load model of the HL93 vehecle, including axle load distribution and overall vehicle dimensions. The HL93 vehecle is a standard design load commonly used in bridge and roadway evaluation, with a total load of 325 kN, distributed across three axles: a front axle load of 35 kN and two rear axles of 145 kN each. The axle spacing varies between 4.3m and 9m, depending on actual conditions. In this study, the load selected for analysis is the 145 kN axle.

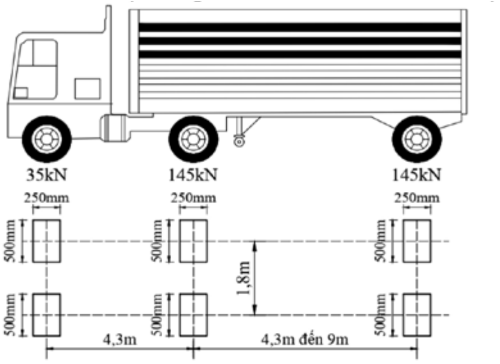


Figure 5. HL93 vehecle axle load

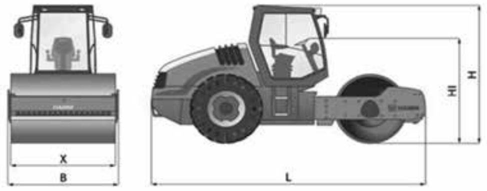


Figure 6. Hamm 3412 roller

According to the studies [11], [12], oil displacement is highest under dynamic loading at low frequencies and gradually decreases as the frequency increases. When the frequency exceeds 5 Hz, soil displacement shows minimal variation. Therefore, this study focuses on analyzing the impact of dynamic loading at three frequency levels - 1 Hz, 3 Hz, and 5 Hz - to assess changes in the subsoil behavior. Additionally, according to [3], the magnitude of dynamic loads ranges from 3% to 11% of static loads. In this study, the dynamic load magnitude is set at an average values of 5% and 10% relative to the static load.

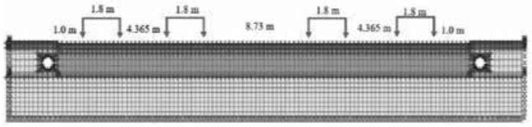


Figure 7. Load arrangement diagram of HL93 vehicle

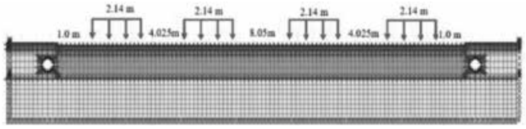


Figure 8. Load arrangement diagram of Hamm 3412 roller

2.6. Finite element method (FEM)

The analysis in FLAC7.0 employs the Finite Difference Method (FDM). FDM discretizes the analysis domain into a grid of square or simple geometric elements and approximates derivatives to compute variable values at grid nodes. FLAC operates based on a Lagrangian approach, allowing the simulation grid to move with the material, enabling the modeling

Figure 9. Model Development Process Using FLAC 7.0

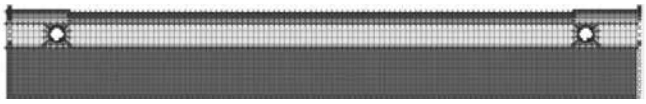


Figure 10. Finalized Model of large deformation and nonlinear problems

3. RESULTS & DISCUSSION

Figure 10, Figure 11, Figure 12 respectively simulate the results of displacement, displacement zones, and stress distribution of the drainage pipe.

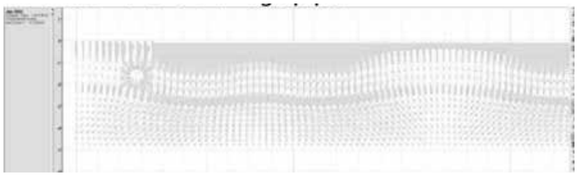


Figure 11. Displacement of the drainage pipe

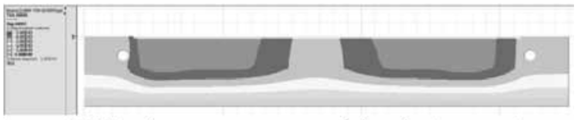


Figure 12. Displacement zones of the drainage pipe

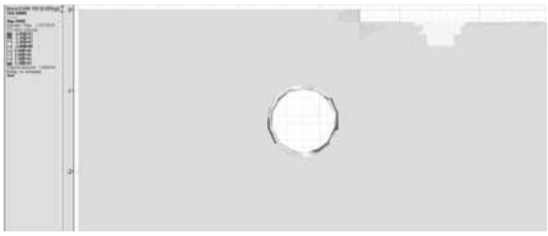


Figure 13. Stress distribution of the drainage pipe

The results from the model cases are presented in Table 4 and Table 5.

Table 4. The results of the Hamm 3412 load

No	Type of Load	Amplitude (%)	Load (kN/m)	Frquency (Hz)	Displacement (mm)	
					X	Y
1	Static	-	31	-	0	2.6
2	Dynamic	5%	31	1	0	5.2
3		5%	31	3	0	5.3
4		5%	31	5	0	5.3
5	Dynamic	10%	31	1	0	5.5
6		10%	31	3	0	5.6
7		10%	31	5	0	5.9

Table 5. The results of the HL93 vehicle load

No	Type of Load	Amplitude (%)	Frquency (Hz)	Load (kN/m)	Displacement (mm)	
					X	Y
8	Static	-	-	1421.6	0	3.5
9	Dynamic	5%	0.1	1421.6	0	4.4
10		5%	0.5	1421.6	0	5.7
11		5%	1	1421.6	0	8.4
12		5%	3	1421.6	0	8.5
13		5%	5	1421.6	0	8.7
14	Dynamic	10%	0.1	1421.6	0	4.8
15		10%	0.5	1421.6	0	6.1
16		10%	1	1421.6	0	8.8
17		10%	3	1421.6	0	8.9
18		10%	5	1421.6	0	9

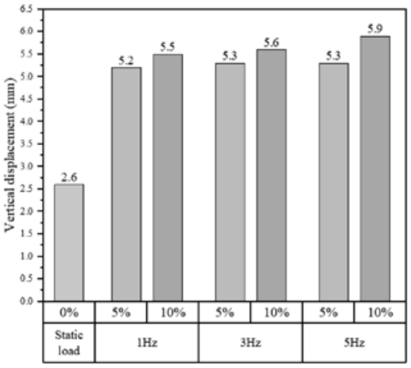


Figure 14. Displacement of the culvert due to the Hamm 3412 roller load

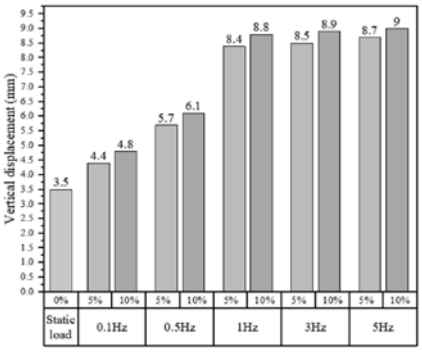


Figure 15. Displacement of the culvert due to the HL93 vehicle load

3.1. The effect of static and dynamic loads on the displacement of the drainage

Under static loading conditions, the Hamm 3412 roller induces a displacement of 2.6 mm, while the HL93 vehicle generates a larger displacement of 3.5 mm (Figure 14, Figure 15). This discrepancy can be attributed to the differences in the load distribution between the two vehicle types. The HL93 vehicle, which has a more substantial structure and greater weight compared to the Hamm 3412 roller, applies a more significant force to the culvert, resulting in a larger displacement. The data presented in the table demonstrates that, under static load conditions, the displacement tends to stabilize, showing minimal variation. This reflects the limited influence of dynamic factors in static scenarios. These findings suggest that, in static conditions, assessing the load-bearing capacity and deformation of the culvert is crucial for ensuring the mechanical integrity of the structure when subjected to a constant, unchanging load.

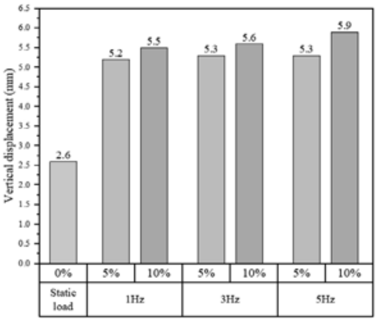
In contrast, under dynamic loading conditions, the difference in displacement between the two vehicles becomes more evident. For the Hamm 3412 roller, displacement varies from 5.2 mm at a 5% amplitude (1 Hz frequency) to 6.1 mm at a 10% amplitude. Similarly, the HL93 vehicle induces a more pronounced displacement change as the amplitude increases, with displacement varying from 4.4 mm at a 5% amplitude to 9 mm at a 10% amplitude. These results highlight the significant impact of dynamic loading, characterized by continuous oscillations and varying intensity over time, leading to greater deformations compared to static loads. Furthermore, this emphasizes the substantial influence of dynamic loads on drainage culverts, particularly in traffic environments where load magnitudes are unstable and fluctuate frequently.

3.2. The effect of amplitude and frequency on the displacement of the drainage

The amplitude and frequency of dynamic loads significantly influence the displacement of the drainage culvert. Among these factors, amplitude is the most critical in both vehicle types. Specifically, at an amplitude of 5%, the displacement of the culvert under the Hamm 3412 roller load varies from 5.2 mm to 5.4 mm (Figure 14), while for the HL93 vehicle, the displacement ranges from 4.4 mm to 8.7 mm (Figure 15). This increase in displacement reflects the effect of amplitude on the intensity of dynamic loading, with higher amplitudes resulting in a greater force exerted on the culvert, leading to more pronounced deformation .

When the amplitude increases to 10%, the displacement of the Hamm 3412 roller continues to increase, ranging from 5.5mm to 6.1mm, while the HL93 vehicle exhibits a more substantial increase, from 4.8mm to 9mm. These results demonstrate that larger amplitudes result in a significant rise in displacement, indicating a considerable influence of amplitude on the structural response. A 10% amplitude particularly amplifies both the oscillatory motion and deformation of the culvert, potentially causing structural damage if not thoroughly considered in the design process.

In contrast, the effect of frequency is less pronounced. Although the frequency of the dynamic load varies from 1 Hz to 10 Hz, the displacement does not change substantially. For instance, at an amplitude of 5%, the displacement of the Hamm 3412 roller varies slightly from 5.2mm to 5.4 mm as the frequency changes, while for the HL93 vehicle, the displacement shifts from 8.4mm to 8.7mm. When the amplitude is increased to 10%, the variation in displacement remains relatively modest despite frequency changes from 1 Hz to 5 Hz. These observations suggest that frequencies ranging from 1 Hz do not have a significant effect on the displacement of the drainage culvert.



The findings of previous studies corroborate these observations. Youssef M.A. Hashash et al. (2001) reported that the dynamic displacement of underground structures is typically 6 to 8 times larger than that under static loads, depending on soil properties and culvert depth. Likewise, Xu et al. (2017) demonstrated that lateral displacement increased from 1.2 mm under static loading to 7.5 mm under dynamic loading at 5 Hz, reflecting an approximate 6.25-fold increase. Similarly, Sakyi et al. (2018) observed that the vertical displacement of underground structures increased from 1 mm under static load conditions to 6 mm under dynamic loading, indicating an approximate 6-fold increase. These studies highlight that dynamic loads generally result in significantly larger displacements compared to static loads, particularly in soft soil conditions.

In the present study, the difference in displacement under static and dynamic loads emphasizes the considerable effect of dynamic loads on the drainage culvert. Displacements under dynamic loading are consistently higher than those under static loading. Specifically, for the Hamm 3412 roller, displacement increases from 2.6mm under static conditions to 5.3mm at 5% amplitude and 5 Hz frequency. Similarly, the HL93 vehicle induces a larger displacement, with an increase of approximately 2.5 times compared to the static condition. These results confirm that dynamic loads, particularly those with high amplitudes, significantly affect the displacement of drainage culverts, thereby increasing the potential for structural instability and reduced drainage efficiency.

4. CONCLUSION

Based on the displacement analysis of upgraded pavements under HL93 and Hamm 3412 roller loads, the following conclusions can be drawn:

(i) This study demonstrates that dynamic loads significantly affect the displacement of the drainage culvert more than static loads. Amplitude is the most influential factor, with larger amplitudes causing a notable increase in displacement, heightening the risk of damage and reducing drainage efficiency.

(ii) Frequency does have an impact; however, the displacement changes little as the frequency varies from 1 Hz to 5 Hz. This suggests that amplitude, rather than frequency, is the primary driver of deformation under dynamic loading.

(iii) The HL93 vehicle induces larger displacements than the Hamm 3412 roller, both statically and dynamically, highlighting that heavier vehicles with stronger oscillatory forces cause greater deformation. These findings emphasize the need to carefully assess the impact of dynamic loads, particularly amplitude, in transportation infrastructure design.

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