An Effective Method for the Determination of the Natural Frequency of piled Pier Segments through Impact Vibration Testing

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ABSTRACT

The Impact Vibration Test (IVT) is an effective, accurate, and fast non-destructive evaluation method to indicate the technical condition of structures through the consideration of the health index. This index is the ratio of measured and designed natural frequencies in the absence of the original measured frequency. However, the determination of the natural frequency of the berth's segments in both numerical and experimental approaches is expensive and time-consuming work. This motivated the present study to develop formulas that allow quick estimation of the natural frequency of the berth's segments based on one of the horizontal frames under various conditions and cases. In order to execute this task, different wharves with various working levels, geological conditions, characteristics, and spring coefficients were examined. A case study for a wharf under a real incident is also provided to show the procedure and demonstrate its effectiveness. Interestingly, the natural frequency of the horizontal frame can be obtained quickly and simply in comparison with that of the berth's segment. Therefore, the proposed formulas are expected to significantly enhance the efficiency of field IVT investigations.

Keywords-open piled pier; natural vibration frequency; impact vibration test; structure health index; port structure evaluation; structure health assessment; technical assessment; technical verification; quality verification

I. INTRODUCTION

Among many non-destructive evaluation methods [1], the Impact Vibration Test (IVT) is an effective approach that evaluates a structure's health based on the natural frequency determined from the structure response due to the excitation of impacts leading to oscillation. IVT was developed by the Japan Railway Technical Research Institute, and CTI Engineering Japan company [2]. It is noted that the first applications of the IVT were on railway bridges in Japan [3], thereafter, it became an effective selection for roads, bridges, ports, and other structures in civil engineering. In particular, the IVT has been utilized to evaluate the health of more than 300 structures in Japan [4], i.e. 362 spread foundations, 129 caissons, and 135 pile foundations. Moreover, the health of the piers of bridges [5-7] and bridges under the effect of the erosion [8] were exhibited by the IVT in China. Furthermore, this method has recently been a preferable selection to assess the technical conditions and health of ports [9-13], and the damage to wharves [14-17]. In the IVT method, the health index, which is a ratio of the natural frequency from measurements and design [3] (in the case of unavailable data for initial measurements just after the structure is put in operation), is an important factor indicating the structure's technical condition. In this study, the design natural frequency of the berth segment is obtained through dynamic analysis using numerical simulation.

Noticeably, almost all new and old ports in Northern and Southern Vietnam are located on soft soil while those located in Central Vietnam are situated on better soil in terms of subsidence. In addition, the design and completion documents of many wharves (e.g. Chua Ve Port, several wharves in Ho Chi Minh City) have not been stored for many reasons. Therefore, it is difficult to reflect the deterioration of the berths compared to the initial design, especially for structures facing incidents or changes in operation conditions.

In addition, the piled piers often made of concrete are frequently exposed to severe environmental conditions, hence, their deterioration rate is commonly higher than that of structures on the mainland. Typical deformation sequences of piled piers are cumulative deformation (due to the corrosion of piles and cracking of the superstructure) and sudden deformation (due to damage to superstructures or fall of bridges under the pressure caused by waves). In order to diagnose and indicate abnormalities in cases of operation condition changes (work with heavier ships compared to the initial design, reduced incoming and outgoing loads, existence of additional cranes with existing loads), incidents or erosion occur, the requirement of a quick evaluation of technical conditions is paramount. The IVT is a feasible, safe, fast, and simple method which can be highly effective. Related to these cases, the recommendation of formulas to quickly determine the natural frequency of the berth segment is necessary, especially for old wharves that lack design and completion documents which is one of the main contributions of this work.

Moreover, the model's outputs are affected by the springs (related to the connection between the pile and soil) wherein their stiffness depends on the accuracy in determining the spring coefficient of impact vibration modal. Additionally, the geology under distinct wharves can be highly different, i.e. in case a comparison between regions in Vietnam, and a comparison between Vietnam and Japan are performed. Previously, the dynamic spring coefficient was recommended to be double [18-21] or three times the static factor with various soil types considered [3, 22]. Another contribution of this study is that during the development of the mentioned formulas, various such conditions were taken into account.

In order to manage the above mentioned objectives, the present work determines a data set of natural frequencies for berth segments and their typical horizontal frames (F_{kn}). Thereafter, equations to calculate the berth segment's natural frequency (F_{pd}) through the horizontal frame's outcome are proposed. This helps not only reduce the time needed to conduct the dynamic analysis model and process measurement data, but also determine the health index of the berth's segments.

II. NUMERICAL DETERMINATION OF DESIGN NATURAL FREQUENCIES FOR BERTH SEGMENT'S AND HORIZONTAL FRAME'S NATURAL FREQUENCY

In the present study, two groups of design dynamic analysis models were created:

- Model group No.1: The spring bearing model group applies boundary conditions to the spring bearings, which means that the simulated spring bearings are for the pile-to-soil connection. Particularly, four types are examined. Model types No.1 (M1) and (M3) employ a dynamic spring coefficient that is double the static coefficient, whereas Model types No.2 (M2) and (M4) utilize a dynamic spring coefficient equal to three times the static coefficient. However, the static spring coefficient was calculated according to the Standard Penetration Test (SPT) index in Models M1 and M2 and according to the Plasticity Index (IL) in Models M3 and M4.
- Model group No.2 (M5): Model boundary conditions are fixed, which indicates simulated rigid restraint for pile-to-soil connection. One model (M5) is applied to this group. It is proposed that Model M5 be only applied to horizontal frames when relevant records are lost, parameters be based on field surveys, and additional geological bore-holes be possible.

In a simple way mentioned in [11, 21], the natural periods of piled piers can be calculated by analyzing their horizontal frames. If the relationship between displacement and small load impact is obtained from horizontal frame analysis, the dynamic spring stiffness can be set as a constant. Consequently, the natural periods and frequencies are obtained from (1) and (2), respectively. Interstingly, to calculate natural periods, the dynamic spring coefficient is normally selected to be double the static spring coefficient. In addition, according to the guidance documents on the IVT [3], the dynamic spring coefficient can be three times the static spring coefficient depending on structure types and geology conditions [10,11].

$$T_s = 2\pi\sqrt{\frac{W}{gK}} \quad (1)$$

$$F = \frac{1}{2\pi}\sqrt{\frac{gK}{W}} \quad (2)$$

where T_s is the natural period of piled piers (s), W is the self-weight and static load per one row of pile group (kN), g is the gravitational acceleration (m/s^2), and K is the spring constant of the piled pier (kN/m).

Determination of the piled pier's design natural frequency can be carried out by the numerical simulation (i.e. a dynamics analysis model) through finite element software, as in [5-9] in which the pile and soil work are simultaneously modeled by spring connections, as observed in Figure 1.

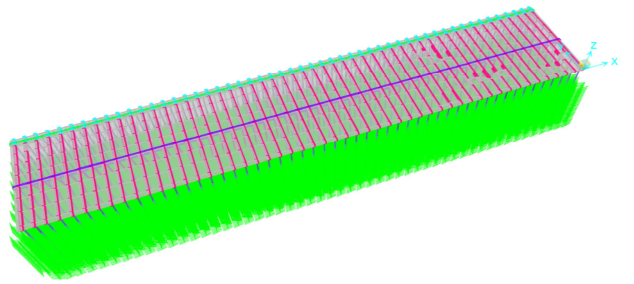


Fig. 1. Impact vibration analysis model of Gemarlink Berth.

The models created by SAP 2000 include horizontal beams, longitudinal beams, and plate elements. Moreover, the weight of cranes is considered to correspond to their real arrangement on the field of the berth's segments.

A. The Natural Frequency of Horizontal Frames

In this section, typical wharves classified into II to special levels from Northern, Central, and Southern Vietnam are examined (see Table I) wherein the capacity in terms of the shipload is from 20.000 to 200.000 DWT. All ports are structures in service for no longer than 20 years. In order to determine the horizontal spring stiffness (K), the linear regression analysis of the displacements and acting horizontal loads in the elastic phase is conducted first. Thereafter, the K coefficient (kN/m) is developed following (3) in which P_x is the horizontal load in the elastic phase (kN) and d_x is the displacement (m). For example, the K = 29.251 kN/m, as shown in Figure 2, for the case of the dynamic spring stiffness of three times the static stiffness computed based on the SPT index (3KSPT).

$$K = \frac{P_x}{d_x} \quad (3)$$

TABLE I. LIST OF SEVERAL TYPICAL BERTHS

No.	Name	Classification		Capacity (10^3 DWT)	Height (m)	Age (y)	Location
		Shipload (SL)	Height				
1	Tan Vu No.1 (TV1)	II	II	20	13.45	14	Northern Vietnam
2	Tan Vu No.2 (TV2)	II	II	20	13.45	14	
3	Tan Vu No.4 (TV4)	II	II	20	13.45	12	
4	Nam Dinh Vu (NDV)	I	II	50	14.00	0	
5	Mipec	I	I	40	17.70	3	
6	Lach Huyen (HICT)	Special	I	80	19.50	5	
7	Nghi Son (NS)	II	I	30	17.00	5	Central Vietnam
8	Cua Lo (CL)	II	I	30	16.5	5	
9	Vung Ang (VA)	I	I	45	17.8	0	
10	Quy Nhon New Port (QNNP)	II	I	30	16.7	19	
11	Cai Cui (CC)	II	I	20	15.7	17	Southern Vietnam
12	SITV	Special	Special	80	22	12	
13	Gemarlink Terminal, Segment No.1 (GEM 1)	Special	Special	200	21.5	2	
14	Gemarlink Terminal, Segment No.2 (GEM 2)	Special	Special	200	21.5	2	
15	Gemarlink Terminal, Segment No.3 (GEM 3)	Special	Special	200	21.5	2	

By using (3), the natural frequencies of the horizontal frame F_{kn} of Models M1 and M2, M3 and M4, and M5 of berths are evidenced in Tables II-IV. Namely, the SPT (Models M1 and M2) and IL (Models M3 and M4) correspond to the cases of determination of the static spring stiffness from SPT [20, 21] and IL [23]. It should be noted that the weight of goods and transports was not considered. Additionally, GEM 1, GEM 2, and GEM 3 are GEM's segments No.1, No.2, and No.3, respectively. For all calculations, g was considered equal to 9.81 m/s^2.

TABLE II. TYPICAL HORIZONTAL FRAMES' NATURAL FREQUENCIES OF MODELS M1 AND M2

No.	Name of berth	W (kN)	K (kN/m)		F_{kn} (Hz)	
			Model M1	Model M2	Model M1	Model M2
1	TV1	4,211	21,087	25,716	1.115	1.232
2	TV2	4,211	20,855	25,370	1.109	1.224
3	TV4	4,173	47,891	53,333	1.689	1.782
4	NDV	8,022	36,335	40,754	1.061	1.124
5	Mipec	7,838	21,479	23,988	0.825	0.872
6	HICT	10,174	55,463	60,821	1.164	1.219
7	NS	6,499	22,982	24,376	0.937	0.965
8	CL	6,453	24,876	27,490	0.979	1.029
9	VA	10,073	55,463	60,821	1.170	1.225
10	QNNP	7,756	29,017	31,963	0.964	1.012
11	Cai Cui	5,388	49817	54385	0.663	0.685
12	SITV	15,312	68179	76046	0.879	0.907
13	GEM 1	10,976	24649	27239	1.516	1.584
14	GEM 2	11,669	28158	31176	1.052	1.111
15	GEM 3	11,939	26464	29251	0.747	0.785

TABLE III. TYPICAL HORIZONTAL FRAMES'S NATURAL FREQUENCIES OF MODEL M5

No.	Name of berth	W (kN)	K (kN/m)	F_{kn} (Hz)
			M5	M5
1	TV1	3,366.6	16,413	1.10
2	TV2	3,366.6	16,413	1.10
3	TV4	3,402.3	16,234	1.09
4	NDV	6,501.6	30,647	1.08
5	Mipec	6,656.9	44,032	1.28
6	HICT	9,442.3	14,652	0.62
7	Cai Cui	4,172.0	33,223	1.41
8	SITV	12,946.0	77,821	1.22
9	GEM 1	9,237.1	28,035	0.87
10	GEM 2	9,505.1	31,546	0.91
11	GEM 3	10,081.2	30,093	0.86

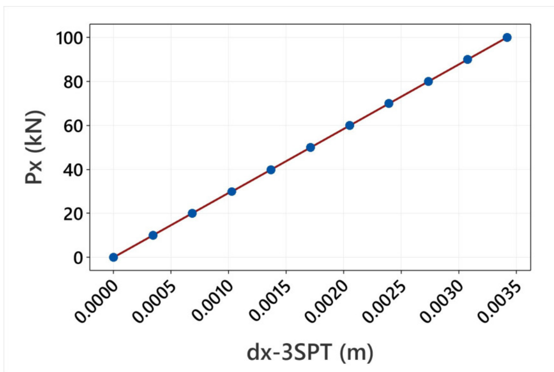


Fig. 2. Relationship between load and displacement from segment No.3's transverse frame analysis (3KSPT) of Gem.

TABLE IV. TYPICAL HORIZONTAL FRAMES'S NATURAL FREQUENCIES OF MODELS M3 AND M4

No.	Name of berth	W (kN)	K (kN/m)		F_{kn} (Hz)	
			M3	M4	M3	M4
1	TV1	4,211.32	37,647	41,007	1.49	1.56
2	TV2	4,211.32	37,647	41,007	1.49	1.56
3	TV4	4,172.95	61,887	66,977	1.92	2.00
4	NDV	8,022.31	47,847	51,733	1.22	1.27
5	Mipec	7,838.33	25,654	27,903	0.88	0.92
6	HICT	10,174.13	50,538	55,074	1.11	1.16

B. The Natural Frequency of Berth Segments

In reality, the geological conditions of berths in the survey reports do not include tests for piles withstanding horizontal forces. Hence, the static spring coefficient is calculated according to the SPT values [20, 21]. Particularly, this coefficient (the factor of the lateral subgrade reaction of the subsoil - k_x in kN/cm^3) can be determined using Chang's method as in (4) where N is the SPT value of the soil around the piles. Consequently, k_x is recommended to be from 3,000 to 4,000 kN/m^3 [21]. However, several surveys did not conduct SPT. Thus, the static spring coefficient is obtained according to the IL [23].

$$k_x = 1500\,\mathrm{N} \tag{4}$$

Consequently, the horizontal design natural frequency is obtained through models created in SAP 2000 for berth segments. The results observed in Table V were calculated with the static spring coefficient determined based on IL, whereas those calculated from the SPT can be seen in Table VI.

TABLE V. TYPICAL BERTH SEGMENTS'S NATURAL FREQUENCIES OF MODELS M3 AND M4

No.	Name of berth	Piled pier segment's natural frequency F_{pd} (Hz)	
		M3	M4
1	TV1	2.887	3.208
2	TV2	0.948	0.998
3	TV4	0.891	0.935
4	NDV	1.141	1.181
5	Mipec	0.995	1.396
6	HICT	0.991	1.033

TABLE VI. TYPICAL PILED PIER SEGMENTS'S NATURAL FREQUENCIES OF MODELS M1 AND M2

No.	Name of Berth	Piled pier segment's natural frequency F_{pd} (Hz)	
		M1	M2
1	TV1	0.937	0.991
2	TV2	0.832	0.883
3	TV4	1.131	1.175
4	NDV	1.158	1.240
5	Mipec	0.885	0.956
6	HICT	0.968	1.017
7	NS	1.055	1.092
8	CL	1.139	1.198
9	VA	1.439	1.510
10	QNNP	0.737	0.762
11	Cai Cui	1.090	0.971
12	SITV	1.339	1.419
13	GEM 1	0.839	0.885
14	GEM 2	0.854	0.900
15	GEM 3	0.831	0.877

III. PREDICTION OF NATURAL FREQUENCIES OF BERTH SEGMENT BASED ON THE HORIZONTAL FRAME

The development of formulas quickly determining the design natural frequency of berth segments is the main aim of the present work. This is essential for structures in service for a long time that lack design and completion documents. Moreover, the task in the current study is also necessary even if ports with design and completion records are carefully stored, but, the geological survey at the design time may not be totally enough or correct, or there are no initial natural frequency data.

The formulas from (5a) to (12) were developed by using the data from 13 piled piers (Table VI) in which the regression approach was deployed to create equations, as shown in Figures 3-7. Consequently, the natural frequencies of berth segments can be predicted based on the natural frequencies of the horizontal frame in the IVT method. Interestingly, the static spring stiffness was determined from the SPT values for all equations. Moreover, Table VII discloses that the reliability of the achieved formulas is guaranteed. In Table VII, CI is the Confidence Intervals, PI is the Prediction Intervals, S is the standard deviation of the distance between the original and fitted data, R^2 is the percentage of variation in the response that is explained by the model, and R^2 (adj) is the R^2 adjusted for the number of predictors in the model compared to the number of observations. R^2 (adj) is calculated from the mean square error and mean square total.

TABLE VII. THE RELIABILITY AND REGRESSION ASSESSMENT

Equation	CI	PI	S	R^2	R^2(adj)
(5a)	95%	95%	0.0601	92.4%	81.1%
(5b)	95%	95%	0.0165	91.2%	78%
(6)	95%	95%	0.0275	87.7%	79.5%
(7)	95%	95%	0.0189	98.9%	95.8%
(8)	95%	95%	0.0280	97.4%	89.7%
(9)	95%	95%	0.0213	100%	99.9%
(10)	95%	95%	0.0023	100%	99.9%
(11)	95%	95%	0.0283	89.6%	74.0%
(12)	95%	95%	0.0032	100%	99.9%

In the formulas, F_{pd2K}, $F_{pd\text{-}2KIL}$, and $F_{pd\text{-}3K}$ correspond to the design natural frequency of berth's segments inspected from Models M1, M3, and M2, whereas F_{kn2K}, $F_{kn\text{-}2KIL}$, F_{kn3K}, and F_{knn} are the design natural frequency of horizontal frames of berth's segments inspected employing Models M1, M3, M2, and M5, respectively. Moreover, from Model M1, (5a) is used for berth segments in Northern Vietnam while (6) and (7) are employed for structures in Central and Southern Vietnam. From Model M3, (5b) is deployed for berth segments located in Northern Vietnam. Additionally, from Model M2, (8) is utilized for berth segments in Northern Vietnam whereas (9) and (10) are employed for structures in Central and Southern Vietnam. Finally, from Model M5, (11) is used for berth segments located in Northern Vietnam and (12) is applied to structures in Southern Vietnam. Moreover, several statistical processing results are illustrated in Figures 3, 4, 5, 6, and 7 for (8), (9), (10), (11), and (12), respectively.

$$\log_{10}(F_{pd2K}) = -254.2 + 768.0F_{kn2K} - 760.1(F_{kn2K})^2 + 248.0(F_{kn2K})^3 \tag{5a}$$

$$\log_{10}(F_{pd-2KIL}) = 0.00883 + 0.0415\log_{10}(F_{kn-2KIL}) - 5.081\log_{10}(F_{kn-2KIL})^2 + 19.53\log_{10}(F_{kn-2KIL})^3 \tag{5b}$$

$$\log_{10}(F_{pd2K}) = 0.052 + 0.695\log_{10}(F_{kn2K}) - 9.006\log_{10}(F_{kn2K})^2 + 55.26\log_{10}(F_{kn2K})^3 \tag{6}$$

$$\log_{10}(F_{pd2K}) = 0.0931 + 1.614\log_{10}(F_{kn2K}) - 3.168\log_{10}(F_{kn2K})^2 - 41.38\log_{10}(F_{kn2K})^3 \tag{7}$$

$$\log_{10}(F_{pd3K}) = 0.1307 + 0.4846\log_{10}(F_{kn3K}) - 24.47\log_{10}(F_{kn3K})^2 \tag{8}$$

$$\log_{10}(F_{pd3K}) = 0.062 + 0.185\log_{10}(F_{kn3K}) + 7.292\log_{10}(F_{kn3K})^2 + 65.69\log_{10}(F_{kn3K})^3 \tag{9}$$

$$\log_{10}(F_{pd3K}) = 0.081 + 1.704\log_{10}(F_{kn3K}) - 1.208\log_{10}(F_{kn3K})^2 - 48.53\log_{10}(F_{kn3K})^3 \tag{10}$$

$$\log_{10}(F_{pd}) = 0.8991 - 26.34\log_{10}(F_{knn}) + 57.84\log_{10}(F_{knn})^2 + 995.3\log_{10}(F_{knn})^3 \tag{11}$$

$$\log_{10}(F_{pd3k}) = 0.025 + 2.115\log_{10}(F_{knn}) + 4.612\log_{10}(F_{knn})^2 - 139.2\log_{10}(F_{knn})^3 \tag{12}$$

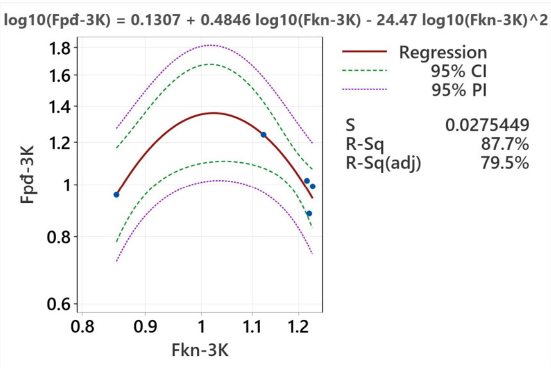


Fig. 3. Relationship between F_{kn-3k} and F_{pd-3K} in Northern Vietnam (M2).

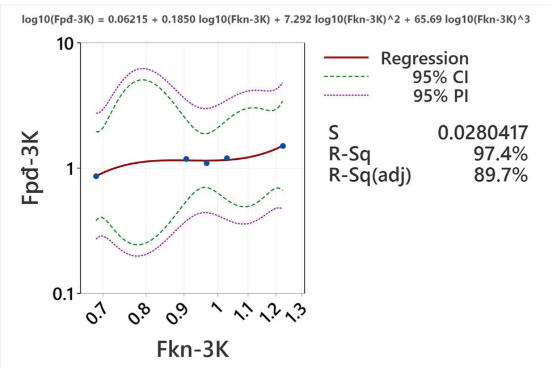


Fig. 4. Relationship between F_{kn-3k} and F_{pd-3K} in Central Vietnam (M2).

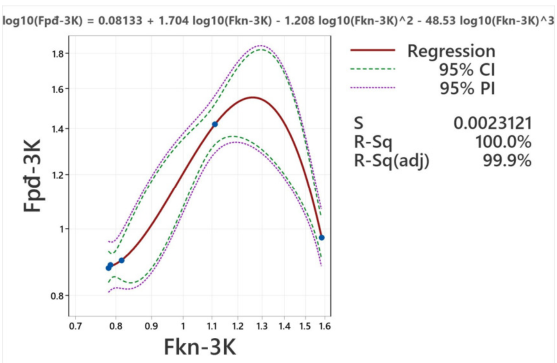


Fig. 5. Relationship between F_{kn-3k} and F_{pd-3K} in Southern Vietnam (M2).

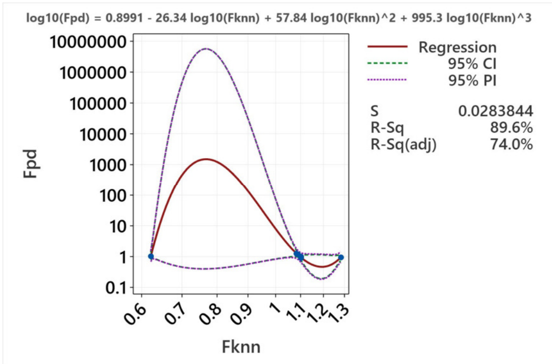


Fig. 6. Relationship between F_{knn} and F_{pd} in Northern Vietnam (M5).

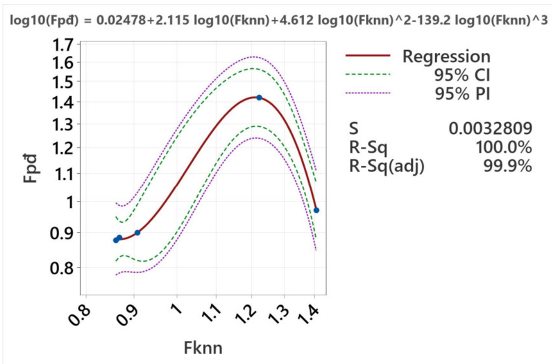


Fig. 7. Relationship between F_{knn} and F_{pd} in the Southern Vietnam (M5).

IV. CASE STUDY

The New Vision ship collided with the Ho Chi Minh wharf (a ship carrying 493 containers, equivalent tonnage of 13,750 DWT). Namely, when the vessel was maneuvered into the piled pier, the left corner of the ship's stern collided with the Ho Chi Minh wharf and shore crane GW5. Thereafter, a visual inspection of the situation revealed that the wheel guard and the plate of the harbor edge had several broken concrete areas, exposing the steel reinforcement. The berth's segment No.3, with the structure illustrated in Figures 8 and 9, is located on the right bank of the Saigon River, a part of the Ho Chi Minh City seaport.

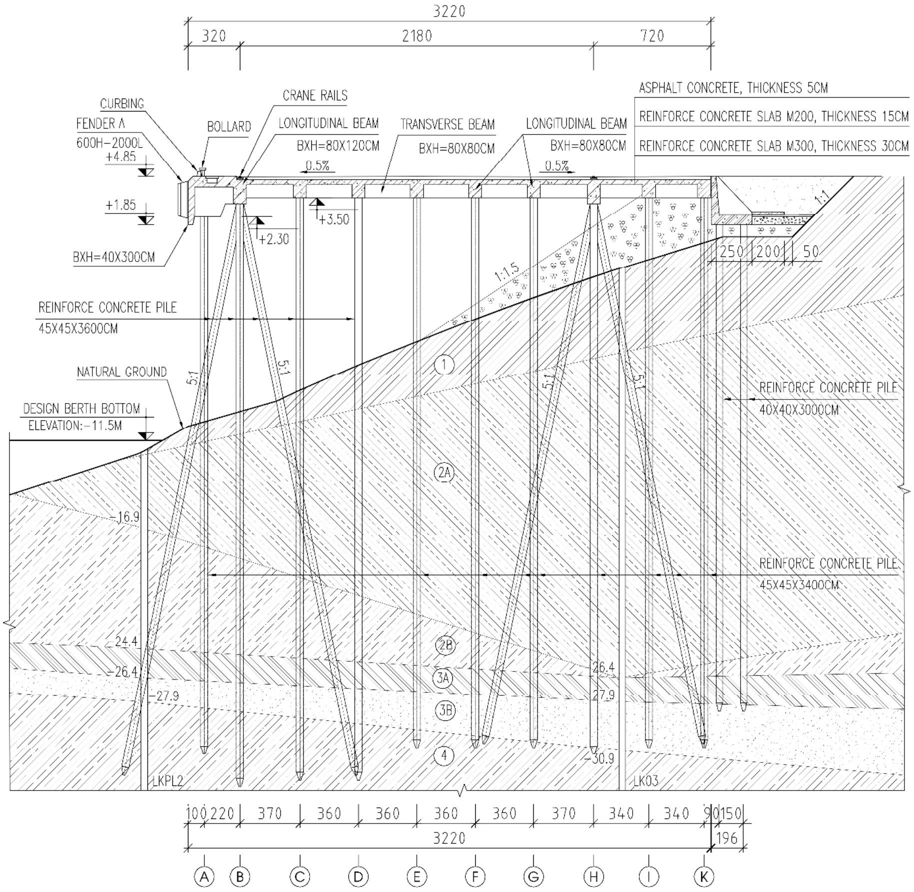


Fig. 8. Transverse section of the berth's segment.

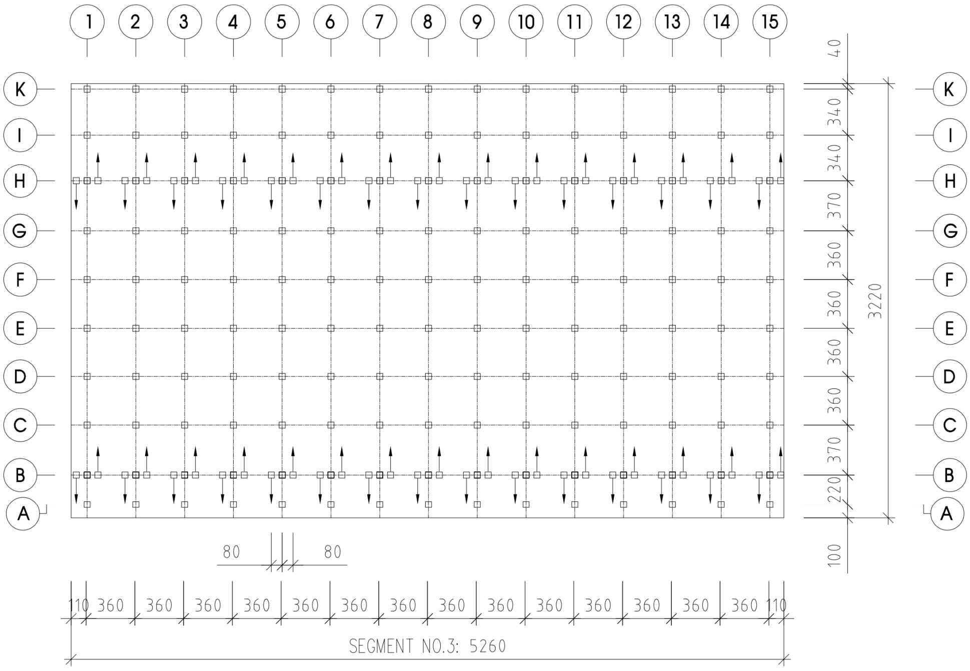
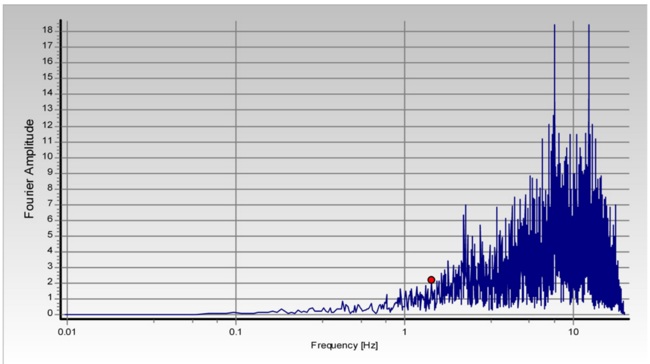


Fig. 9. Plan view of the berth's segment.

It should be noted that the piled pier is approximately 24 years old and the berth consists of five segments. The berth length and width are 203.4 and 32.2 m. The design bottom elevation of the berth is - 11.5 m, whereas the top elevation is + 4.85 m. All components are made of reinforced concrete with a design compressive strength of 30 MPa. Notably, the dynamic spring coefficient is 14,998 kN/m, three times the static factor. In relation to the geological conditions, as portrayed in Figure 8, stratigraphy includes five layers. Namely, Layer 1 is a brown-gray and cement-gray clay mud mixed with dark brown vegetable humus and a flowing state. Layer 2a is a cement-gray clay mud mixed with a lot of organic humus, while Layer 2b is a fine-sandy clay mud with a green-gray color and flowing state. Remarkably, Layer 2b is a weak soil layer with a thickness of 8 to 20 m. Layer 3a is a gray-brown sandy clay with yellow veins and a soft plastic state, whereas Layer 3b is a medium to coarse-grained sand with white-gray colour and a few pebbles. Finally, Layer 4 is a red-brown clay mixed with grit and a soft to semi-hard plastic state.



Fourier and Power Spectra

Frequency	Period	Fourier Amplitude	Fourier Phase	Power Spectru
1.42578	0.70137	0.69333	-0.63937	0.00047
1.43555	0.69660	1.90137	0.24534	0.00351
1.44531	0.69189	2.17606	1.51399	0.00460
1.45508	0.68725	0.93715	-0.52035	0.00085
1.46484	0.68267	1.49682	0.66745	0.00218
1.47461	0.67815	0.96923	-0.46725	0.00091
1.48438	0.67368	1.24346	1.46183	0.00150
1.49414	0.66928	1.58317	0.55210	0.00244
1.50391	0.66494	0.25279	-1.02469	0.00006
1.51367	0.66065	1.04185	-0.17203	0.00106
1.52344	0.65641	0.41303	-1.01063	0.00017

Fig. 10. Determination of the horizontal measured natural frequency.

Thereafter, by applying the numerical approach, F_{kn} is determined as 0.88 Hz. It should be noted that this wharf is located in Southern Vietnam, hence, according to (10), F_{pd} is 0.978 Hz. The filed IVT was also conducted, and then, the measured natural frequency of segment No.3 was determined as 1.44 Hz at a phase shift angle of 90^o using Fourier transform, as depicted in Figure 10 [3-7, 13, 24, 25]. In order to identify the natural frequency types that can appear in the measured data (e.g. from the structure, electric, anchor line, or win), the exclusion method was deployed to determine the frequency. Moreover, the data range was used to extract the natural frequency in which the structure's vibration is minimal to be affected by the impact force, leading to only natural vibration in this range.

After that, the health index was determined as 1.47 (the ratio of 1.44 and 0.978). According to [3], the structure's health after an incident is classified as of S level which means that the health condition of the structure is still good and the decline of the natural frequency needs to be continuously monitored. This is consistent with the real situation of the structures and results from other inspections.

V. CONCLUSIONS

In the present study, both numerical and experimental approaches were applied to investigate typical berths located in Northern, Central, and Southern Vietnam. The main drawn conclusions were:

- The current work proposes equations to quickly determine the natural frequency of the berth's segment from the natural frequency of the horizontal frame. The design natural frequency is employed, which is more practical in common cases where previous historical data and standard natural frequency are unavailable. Therefore, this study's results help the IVT become more effective and practical in field inspections.
- The equations proposed by the regression analysis were determined considering various geological conditions representing actual regions in Vietnam. Hence, these equations are expected to be effectively and widely applied to real inspections with similar geological conditions described in the present work not only in Vietnam, but also in other countries.
- The equations provided are based on the berths using inclined piles, whereas the berths with vertical piles were previously examined. Thus, the equations developed in this study are expected to be more accurate for the berth with inclined piles.
- A case study was also conducted for a berth after an incident. The results demonstrated the effectiveness of the proposed formulas as well as the procedure recommended for structures under sudden damage.
- Although several achievements are indicated in the current study, further studies with more data under different conditions such as the soil, structure, and other damage of the wharves to update and verify the proposed equations should be conducted.

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