QUANTIFICATION OF MICRO-VIBRATIONS IN A SEISMICALLY ISOLATED WHARF UNDER SERVICE LOADS

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Abstract

In the last decades seismic isolation has been widely used for protecting new wharves due to its effectiveness and the simplicity of the analyses and computational efforts involved (isolated wharves resemble a single degree of freedom system with a lumped mass supported by piles). It is well known that seismic isolation significantly reduces the seismic action by decoupling the movement of the deck from the piles, lengthening the fundamental period of the structure and providing additional damping. However, an important phenomenon may be observed in actual wharves operating under service load: the vibrations of the superstructure when subject to forces generated above the isolation system.

In this paper the quantification of the vibrations in an isolated wharf is performed by measuring the accelerations in different points of the deck in the presence of cranes unloading ships with a cargo of coal usually ranging between 60,000 and 180,000 tons. Frequency domain analysis techniques were used to obtain characteristic frequencies, velocities and displacements of the structure. Also, a system identification using the Power Spectral Density was implemented to check some of the model's theoretical assumptions.

It was observed on site that the forces that produced the vibrations were originated by off-center lifting of the material during the operation of the cranes. During the unloading of the ships, the cranes lower the empty shovels into the vessels prior to lifting the material. However, the oscillating movement of the shovels gets the cables out of plumb when the shovels reach their resting position; so when the material is raised by the fully loaded shovels, the inclination of cables create a horizontal thrust that excites the systems above the isolation interface.

The wharf under study is provided with 20 rubber isolators and 20 lead rubber isolators, and it is located in a coastal area of northern Chile. In our research, the first concern was the fatigue life of the isolator's lead core, but the results from the equations presented in a previous research work [1, 2] showed that no fatigue problems in the short term are expected (no cracks before 4 years of normal operation). However, a full inspection was recommended after 10 years in order to evaluate the medium and long term effects of micro-vibrations which were deemed not negligible, with a conservative estimation of crack penetration in the lead core of 3mm after 10 years, and 27mm after 50 years (service life). Hence, the cracks theoretically could extend approximately 22mm into the original lead core (100mm of diameter) by the time the service life of the structure is attained.

The Fourier Power Spectra was used to separate the vibrations into the participant frequencies to get a representative number of cycles. The Amplitude Spectrums of the recorded data showed that the measured vibrational phenomenon was complex and difficult to represent, so conservative estimations were adopted. The vibrations were generated by a series of impulsive forces which activated a wide range of frequencies (the shorter the impulse, the wider the activated range of frequencies). Some values obtained after 6 months of measurements were a maximum absolute displacement of ±4mm on the wharf slab, and an average equivalent sinusoidal displacement of ±0.5mm on the slab level at a frequency of 0.7Hz during loading. The ±0.5mm displacement on the slab was associated to ±0.32mm of isolators effective displacements. Also, a system identification was performed using the environmental white noise to calculate the Power Spectral Density with the estimation given by the Peridiogram [3]. The goal of this identification was to obtain the frequencies of the fundamental modes for comparison.

Finally, some workers discomfort was observed, but after the analysis no additional structural problems were discovered, i.e., steel structure fatigue, rubber isolators fatigue or facilities damage from micro-vibrations can be disregarded.

Keywords: seismic isolation, micro-vibrations, service loads, fatigue, frequency domain analysis

1. Introduction

The pile-supported wharves are very common and essential structures in many countries. As such, efforts to increase their level of protection against seismic events has been a major concern over the recent decades. The approach of traditional seismic design strategies has consisted of using the ductility of the structural elements to dissipate energy and reduce the seismic forces. This assumption implies that damage is expected but a certain performance goal is achieved (e.g., immediate occupancy, life safety, etc.). Since wharves are critical structures and the condition of no-damage is preferred, the use of seismic isolation is a good alternative to avoid significant damage and effectively achieve the target of immediate occupancy. There are some researches [4, 5] that state the benefits and disadvantages of the seismic isolation in pile-supported wharves, but they focus on the seismic performance and the large displacements associated with strong motions. However, there is one phenomenon that must be considered for the serviceability analysis of the structure: structural vibrations when the wharf is subject to forces acting above the isolation interface during normal operation of heavy mechanical equipment, such as cranes. These vibrations where observed in an actual wharf - constructed in 2016 - located in a coastal area of northern Chile, and they were measured and analyzed to be presented in this paper.

The vibrations were measured during a period of 6 months and the acquisition of the information was made by 4 accelerometers (sampling rate of 200 Hz) located in different critical positions. The accelerations were transformed to velocities and displacements in time. Also, the main participant frequencies of the recorded excitations (Power Spectrum) were obtained by Fourier analysis.

The focus of the study was the evaluation of the fatigue life of the isolators and steel structure under the presence of the micro-vibrations. The fatigue life of the typical steel elements is well known but the fatigue life of the lead rubber isolators is a field with little research. However, there are some previous works [1, 2, 8] that are focused on the fatigue life of the lead under micro vibrations, so they were used as a reference to calculate the crack growth and the expected fatigue life of the isolators lead core. The fatigue life of the rubber was also investigated using the information available [6, 7] but the failure of this type of material was ruled out.

As a result, this research relates the actual behavior of a seismically isolated wharf by quantification of its micro vibrations and connecting them to the theoretical knowledge in the field of the fatigue life of the isolator's lead core. These micro vibrations are usually neglected during the design process but in some cases, they can cause serious problems of serviceability if they are large enough to produce fatigue problems or discomfort among workers.

2. Description of the Actual Wharf

The structure under study is an open-type wharf supported by steel piles. It has 20 rubber isolators and 20 lead rubber isolators placed between the superstructure (made of steel beams and a concrete slab) and the substructure (made of steel piers with steel beams on top). Some of the piers are inclined so the substructure has a significant lateral stiffness. A cross section of the wharf geometry is shown in Fig. 1.

On top of the concrete slab there are two cranes which move along the structure so variations in the mass distribution can be observed in the dynamic system. This condition was taken account of in this research as vibrations were recorded for wide range of different positions of the cranes. The wharf operation is not permanent, and it only occurs when the cranes must unload the ships which bring coal for a thermoelectric power plant adjacent to the wharf.

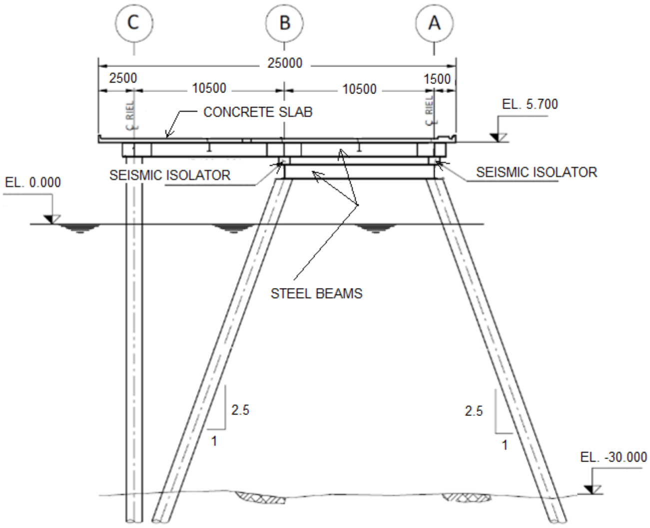


Fig. 1 – Cross section of the wharf

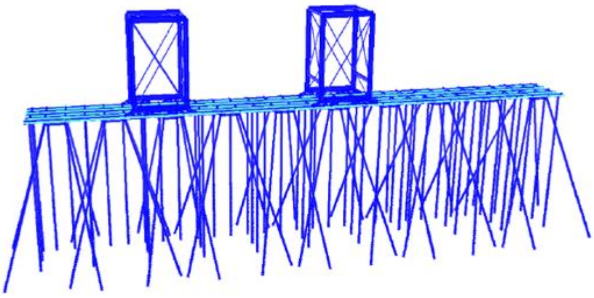


Fig. 2 – 3D Model of the wharf

3. Source of Vibration in Normal Operation Condition

After the onsite observations, it was concluded that the main source of vibration was a horizontal thrust force that excites the cranes, and consequently, the whole superstructure. This force is generated by the off-center lifting of the material. The shovel sways while descending to take the coal, so the shovel resting positions right before loading the coal is normally eccentric with respect to the vertical. Therefore, the lifting starts with the cables having a an inclination that creates the vibrational horizontal force H shown in Fig. 3.

Other sources of vibration were the accelerations of the masses involved in the process, but they were of second order compared to the force described above.

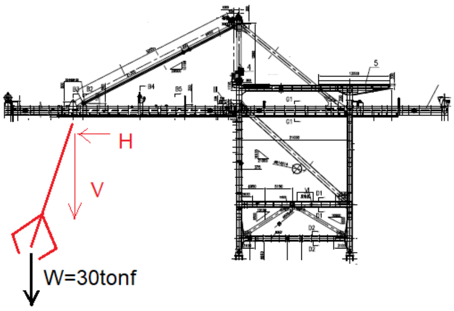
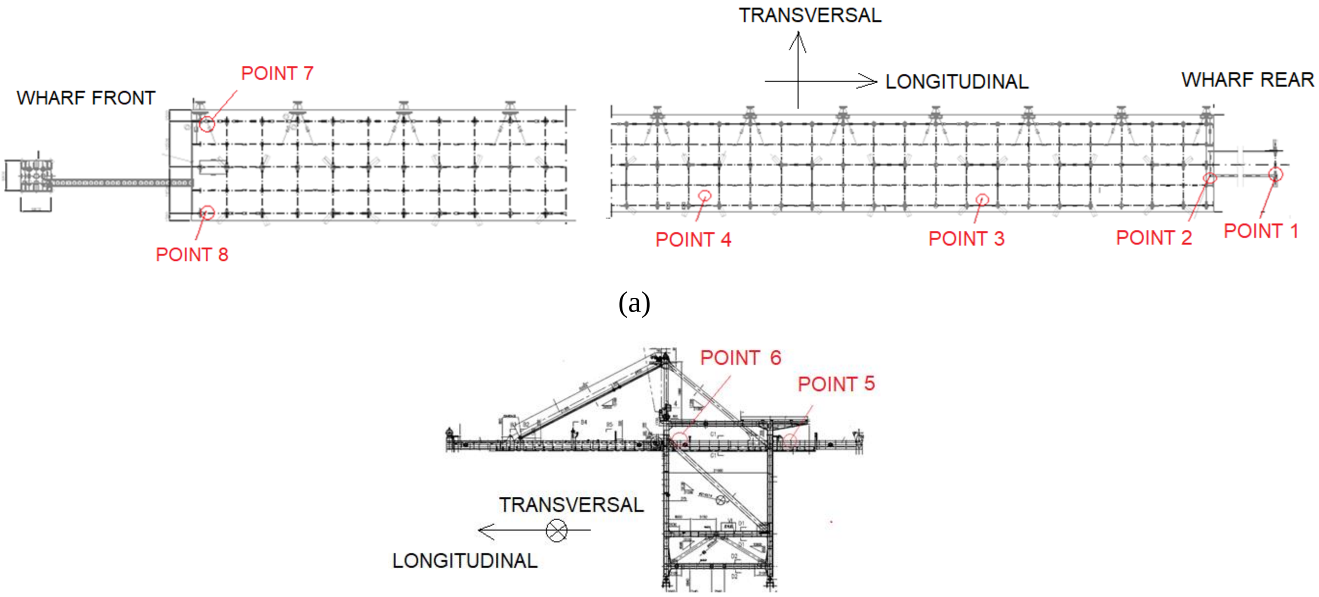


Fig. 3 – Horizontal force H from the off-center lifting

4. Measurement of the Micro-Vibrations

The selected points to record the accelerations (in the 3 main directions: longitudinal, transversal and vertical) were distributed along the wharf slab and cranes. During a period of 6 months a total of 65 records were made for different cranes positions during the most critical days of normal operation when the cranes were working at full capacity and speed.



(a)

(b)

Fig. 4 – Measurement points: (a) Wharf slab plan view (b) Crane elevation

After a few trial measurements, it was observed that the main vibration frequencies were in the range of 0.5Hz-5Hz. It was supposed conservatively that environmental noise was present up to 100 Hz (this noise must be captured and filtered). As a result, the N_{YQUIST} frequency for the measurements was set in 100Hz so from Eq. (1) a sampling rate of dt=0.005s was used. The resolution adopted was Δf=0.1Hz so from Eq. (2) the minimum number of points for each record was N=2000. The records in time domain were converted to frequency domain using FFT (Fast Fourier Transform) and all frequencies below 0.5Hz and above 5Hz were filtered out. It is important to mention that the complex symmetry around N_{YQUIST} has to be forced computationally. The frequencies above N_{YQUIST} get aliased into the lower range and cannot be easily filtered.

$$N_{YQUIST} = 1 / (2 \cdot dt) \tag{1}$$

$$\Delta f = 1 / (N \cdot dt) \tag{2}$$

The velocities and displacements in frequency domain were obtained from accelerations applying the well-known transfer functions $1/(i \cdot \omega)$ and $-1/\omega^2$ for velocities and displacements respectively. The results in frequency domain were transformed back to time domain using the tool IFFT (Inverse Fast Fourier Transform). Notice that the amplitude spectrums given by MATLAB FFT should be scaled appropriately in order to obtain representative values of frequency displacements or velocities (usually a scale factor of 2/N or 4/N depending on the "windows" applied to the data for a single sided spectra, where N is the length of the record). A summary of the main results in both time and frequency domain are shown below.

Table 1 – Maximum Absolute Displacements

Position	**Direction**	**Maximum Displacement [mm]**
On Wharf Slab	Transversal	4
	Longitudinal	2
Crane	Transversal	12
	Longitudinal	6

A couple of amplitude spectrums obtained from different records for critical point #2 are shown in Fig. 5 and 6. The maximum absolute displacement (superposing all frequencies) corresponds to 4mm and the main participant frequencies are around 0.6Hz-1.12Hz with a maximum frequency displacement of 0.5mm.

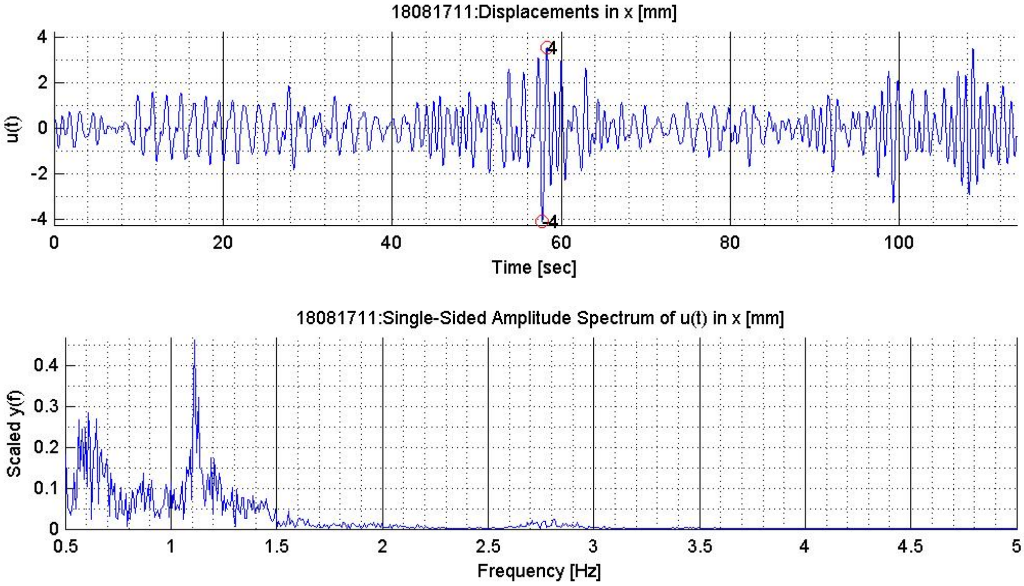


Fig. 5 – Transversal Displacement v/s Time and Amplitude Power Spectrum [mm] for the critical point #2

Since there is not a well-defined sinusoidal pattern to describe the vibrations, a conservative approach was adopted to obtain a representative value for an equivalent sinusoidal movement. From the critical record of Fig. 5 a beat frequency (superposition adding amplitudes) given by Eq. 3 yields to a value of $f_{beat} \approx$ 0.52Hz considering the two most significant amplitudes (0.6Hz and 1.12Hz).

$$F_{beat} = |f_1 - f_2| \tag{3}$$

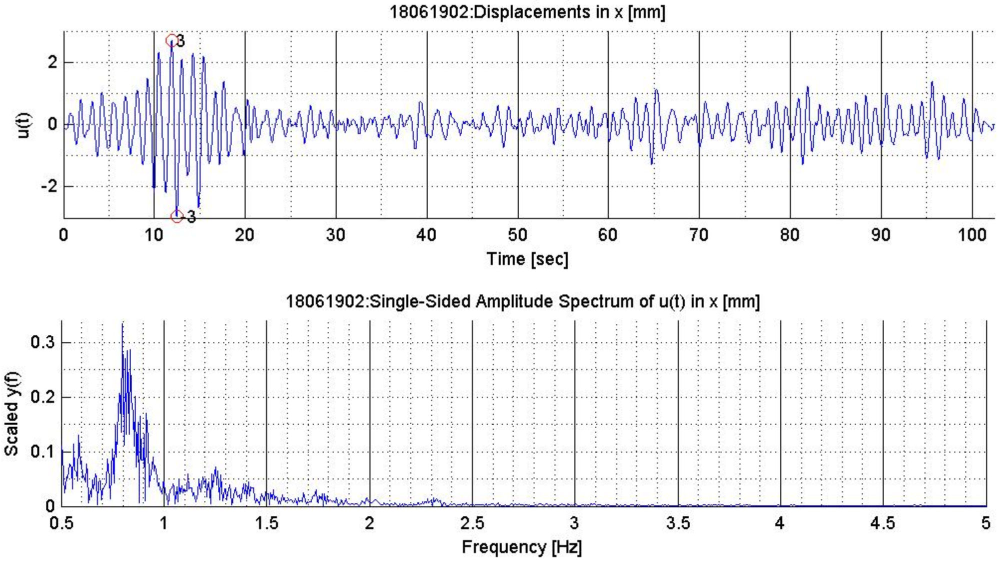


Fig. 6 – Transversal Displacement v/s Time and Amplitude Power Spectrum [mm] for the critical point #2

Repeating the calculation shown above for not all but the most critical records (only for points on wharf slab due to the crane vibration analysis was not in the scope of this research) and applying conservatively a safety factor of 1.25 to increase both frequency and displacement, a frequency value of 0.7Hz and a maximum displacement amplitude of ±0.8mm can be assumed as maximum sinusoidal equivalent superstructure transversal vibration on the slab level. The longitudinal and vertical directions have smaller displacements, so the results of this paper are presented based only on the transversal direction.

In addition to the spectral analysis, the number of cycles were counted for every record in time domain, and an average frequency of approximately 0.7Hz was also obtained confirming that the value of 0.7Hz adopted as a representation of the whole vibration is appropriate.

5. Identification of the Fundamental Frequencies of the Structure

The identification of the experimental structure fundamental frequencies was performed using the environmental white noise and the Power Spectral Density estimation given by the Peridiogram and reduction of variance according to Bartlett [3].

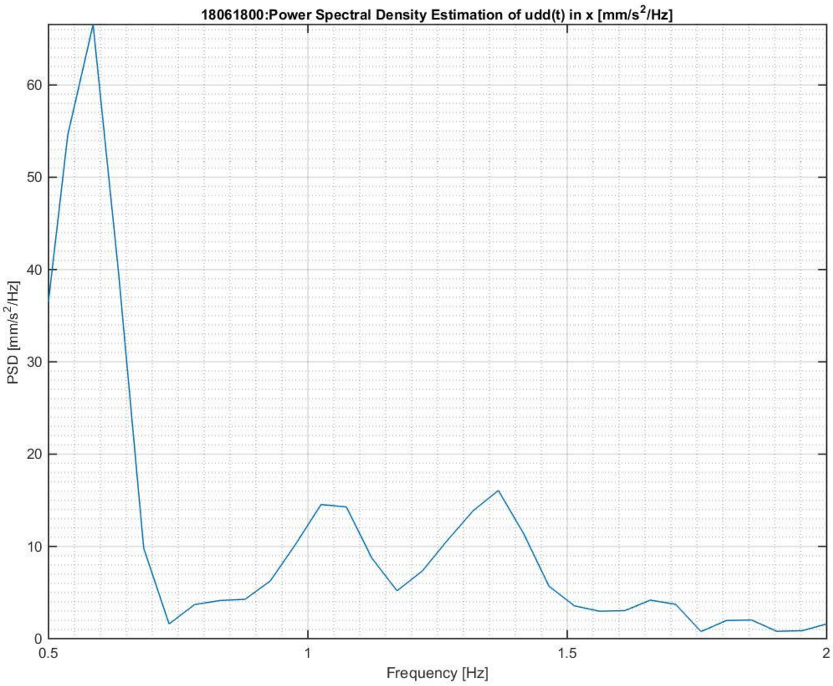


Fig. 7 – Power Spectral Density estimation from white noise– Transversal direction

The Fig. 7 shows that the main frequencies are 0.6Hz, 1.1Hz and 1.35Hz. This plot helps to explain the complex vibration of the wharf. The source of the vibration is a series of impulsive forces arising from the shovel operation which activate a large range of frequencies as shown in Fig. 8. because the traditional Fourier Transform of a rectangular pulse is similar to that of the measured data (the shorter the duration of the force, the larger is the range of frequencies activated by the impulses). Therefore, this series of pulses activate during the duration of the operation a vibrational movement in the main frequencies of the system. This complex phenomenon can be represented conservatively by a sinusoidal movement of frequency 0.7Hz and a maximum displacement amplitude of ±0.8mm on the slab critical position which is point #2 of Fig. 4.

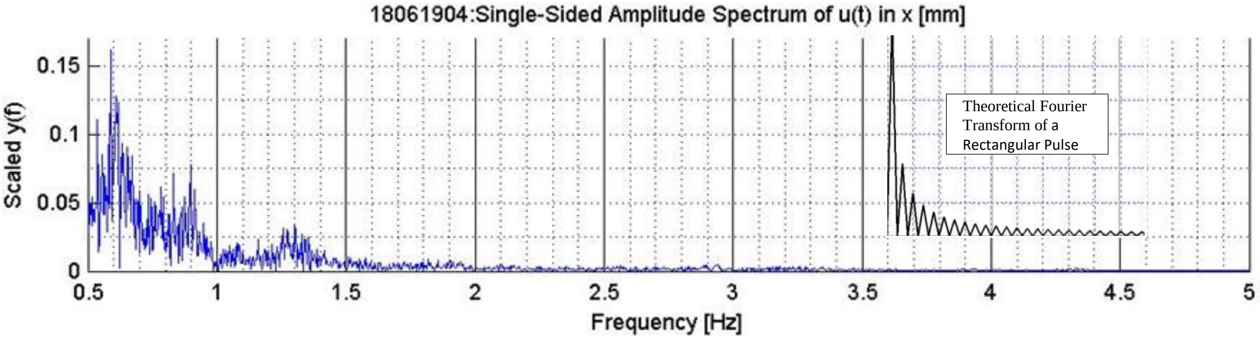


Fig. 8 – Typical Amplitude Spectrum for the data gathered in the wharf

6. Analysis of the Fatigue Life of Seismic Isolators

The number of cycles per year of the wharf vibrations were obtained based on the 0.7Hz frequency of the equivalent sinusoidal vibration present only during 40 seconds of each shovel operational cycle. The shovel capacity is 30ton, and the wharf is designed to transport 1,750,000 ton per year, working with 1.5 shovels on average. The previous numbers yield to a total number of micro-vibration cycles of 1,000,000 cycles / year.

The vibrations equivalent maximum amplitude value of ±0.8mm on the slab level stated on the previous section is the average but only of the most critical records for the critical position #2. Repeating the calculation considering all the data, the results is that the average amplitude of all records is ±0.5mm for this same critical position, so this average value will be used to calculate the fatigue life. To obtain the effective displacements of the isolators (relative displacement between substructure and superstructure), a 3D model was elaborated including the lateral stiffness of all elements. From the model was found that a critical average vibration of ±0.5mm on the slab level produces an effective average deformation of ±0.32mm in the most critical isolator.

Considering the 1,000,000 cycles/year of micro-vibrations with isolators average effective vibration amplitude of ±0.32mm, the only element of the whole structure than can have fatigue problems is the lead core of the lead rubber isolators. The rubber and the traditional steel elements are subjected to such small vibrational forces that the fatigue is of no concern [6, 7]. The Eq. 4 and Eq. 5 [2, 8] give an estimation of the fatigue effect, where N is the number of cycles to failure and N_c is the number of cycles to crack occurrence, and A is the amplitude in [mm].

$$N = 1.39\cdot10^{6}\cdot A^{-1.82} \tag{4}$$

$$N_c = 4.81\cdot10^{4}\cdot A^{-1.87} \tag{5}$$

Using A=±0.32mm (average of all records in critical position #2), failure is expected after 110 years and appearance of first cracks after 4 years. Also, the expected crack depth (penetration in the lead core) is 3mm after 10 years, 27mm after 50 years, 63mm after 110 years. The previous numbers were obtained using the Eq. 6 for cracks growth of lead dissipators under micro-vibrations given by reference [2], where V_c is crack propagation speed [mm/cycles] and A is the vibration amplitude [mm]. It is clear that the lead core fatigue cannot be neglected in the case of the wharf under investigation, but the expected crack is small taking account of the fact that the isolator lead core is 100mm diameter; therefore, after a service life of 50 years, only a crack penetration of 27mm is – conservatively – expected, leaving about 78% of the lead area with no damage. The recommendation given to the owner of the wharf was only the inspection of the critical isolators after 10 years of the wharf operation. The detection of no-cracks is the best scenario, but if cracks smaller than 3mm are found during this inspection, the wharf´s safety is anyway guaranteed. A crack penetration larger than 3mm after 10 years would mean a damage larger than the predicted by this research, so in this case the replacement of the damaged isolators was recommended.

$$V_c = 8.39\cdot10^{-5}\cdot A^{1.72} \tag{6}$$

Conclusions

In this paper the quantification of the vibrations in an actual isolated wharf is performed by measuring the accelerations in several points of the wharf slab when the cranes are unloading the ships. Frequency domain analysis was used to obtain characteristic frequencies, velocities and displacements of the structure. Also, a system identification using the Power Spectral Density was implemented to check some of the model's theoretical assumptions.

It was found that the average representative effective vibration amplitude is ±0.32mm for the most critical isolator. The vibrations were measured during a period of 6 months and the acquisition of the information was made by 4 accelerometers (sampling rate of 200 Hz) located in different critical positions. Considering the estimation of 1,000,000 cycles/year of micro-vibrations for the wharf operation, the only element of the whole structure than can have fatigue problems is the lead core of the lead rubber isolators. The rubber and the traditional steel elements are subjected to such small vibrational forces that the fatigue is of no concern. However, the crack penetration in the lead core is small compared to the lead area (100mm of diameter) because the crack depth is expected to be only 27mm after 50 years of service according to the formulas given by previous research [1, 2, 8]. Finally, after completing the analysis of the structure, the recommendation to the owner of the wharf was only the inspection of the lead rubber isolators after 10 years of wharf operation. The detection of no-cracks is the best scenario, but if crack penetrations smaller than 3mm are found during this inspection, the wharf´s safety is anyway guaranteed. Only the observation of cracks depths larger than 3mm after 10 years would mean a damage larger than the predicted by this research, so in this case the replacement of the damaged isolators was recommended.

7. References

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