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COMPREHENSIVE VIBRATION ANALYSIS OF DRIVEN PILES AT AN INDUSTRIAL DEVELOPMENT SITE IN KAZAKHSTAN: 9 IMPLICATIONS FOR CONSTRUCTION SAFETY AND ENGINEERING PRACTICES

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ABSTRACT: The installation of piles at construction sites produces vibrations that may extend for hundreds of meters from the location of the pile. Depending on their proximity to this activity, these vibrations can induce damage to nearby structures. The results of a vibration monitoring study that was performed at a water treatment plant in the Republic of Kazakhstan are presented. The goal of this study was to monitor these vibrations at different distances from the point of pile driving. Vibrations were measured at five locations during the driving of three 12 m long prefabricated concrete piles. Since the soils present at the site were problematic, and since vibration monitoring studies are site-specific, the present study fills a gap in vibromonitoring data for such sites. The largest vibration velocities were measured when the piles were driven to depths of approximately 5 to 6 m. The presence of other building foundations at the site affected the magnitude and distribution of the measured velocities. The highest vibration speeds and frequency of vibration did not exceed the requirements of DIN 4150-3. The massive foundation at Point 3 in this vibration study reduced the magnitudes of the vibration velocities and made the three orthogonal velocity components more nearly equal. This, in turn, reduced the effect of vibration on nearby buildings.

Keywords: Vibration monitoring, Pile driving, Geophone, Vibration velocities

1. INTRODUCTION

The installation of steel and concrete piles, sheet piling, produces vibrations that may extend hundreds of meters from the location of the pile. Over time, individuals have become increasingly intolerant of such activities. This, in turn, has increased public pressure on governmental agencies to choose alternative construction methods that, if possible, avoid the vibrations associated with pile driving. Indeed, in many European countries, pile driving is viewed as being ill-suited to urban environments due to the noise and ground vibrations created during installation, which can lead to damage to neighboring structures [1].

Pile driving is known to be one of the noisiest construction activities that may affect individuals located a long distance from its source. Noise from pile driving rarely, if ever, produces actual structural damage [1]. The aforementioned annoyance may, however, cause individuals to seek out perceived damage in structures surrounding the source of the noise and vibration.

On impact, the energy from the hammer is transferred to the pile. It is then distributed between the rebound of the hammer, elastic deformation of the pile, elastic and plastic deformation of the cushioning material, penetration of the pile, and the elastic and plastic deformation of the soil surrounding the pile.

The elastic deformation of the soil is propagated as elastic waves [2]. Within a homogeneous, isotropic, linear elastic continuum, two types of waves can propagate, namely body and surface waves [3]. Body waves consist of compression (P) waves and shear (S) waves. The surface wave of primary interest is the Rayleigh (R) wave.

In saturated soil, P waves will travel solely through the fluid phase, as the pore fluid is essentially incompressible. Since fluids have no shear strength, the velocity of S waves is a function of the elastic properties of the soil skeleton [3]. Once body waves arrive at the surface of a homogeneous, isotropic, linear elastic half-space, R waves are produced.

In an idealized pile driving scenario, the tip of the pile can be thought of as the source of wave generation. As the pile is driven, spherically expanding body waves travel outward to the soil surface, where they are reflected and/or refracted, leaving R waves that expand on cylindrical fronts near the ground surface [3]. As the waves expand outwards, they encompass an increasing volume of soil, thereby lowering their energy density through geometric damping. As body waves expand on a spherical front, their decay is much more rapid than that of surface waves [3]. Vibrations due to pile driving are also attenuated by frictional damping. The contribution of frictional characteristics of the soil is, however small as compared to the geometric component.

The attenuation of particle velocity and acceleration can be computed theoretically from the kinematic energy. Various equations for predicting the peak particle acceleration have been proposed [4-6]. These, however, can only be used to describe the shape of the attenuation curve once a peak particle acceleration value at some point is known.

During the past 35 or so years, developing trends in important aspects of blast and construction vibration monitoring and control have been identified through consideration of research and consulting experience. The regulatory criteria used to assess the impact of vibrations associated with pile driving vary throughout the world, for example SP 305.1325800.2017; GOST R 52892–2007; GOST R 53964–2010 (Russia); DIN 4150–3:1999 (Germany); BS 7385–2:1993 (UK); NS 8141:2001 (Norway).

The vibrations due to pile driving can induce stresses in structures that can lead to damage. Vibration damage can be categorized as follows [7]:
1) Direct vibration damage – R waves propagating through the elements of a building, exposing one or more of those elements to ultimate tensile or shear stresses. Typically, weak mortar and plaster are among the first elements to experience damage. Vibrations can also lead to cracks in walls, ceilings and floors of buildings. Since these often require that repairs be made to the structure, they increase maintenance costs;
2) Indirect vibration damage – vibration waves travelling through the foundation displace it in a manner detrimental to the structure. When poor quality soils are subjected to dynamic effects, their physical and mechanical properties can be affected. Due to fatigue effects, the repeated stressing from the hundreds of blows required to drive a pile can potentially exacerbate damage coming under both of the above categories.

Vibration monitoring as a method of pile impact assessment is becoming more widely used [8-10].The damage potential of pile driving depends on the induced displacement and frequency of the vibration. Neither of these two characteristics alone will damage a structure. Instead, it is the combination of the magnitude of the dynamic displacement and the frequency of the vibration that cause damage.

Vibratory monitoring of pile foundations control in the present study was performed at five locations located at unequal distances from a particular pile. Vibration velocities were measured in all three coordinate directions using a three-dimensional geophone. The results were compared according to the requirements of DIN 4150-3 and the permissible distances of the pile driving location were determined experimentally based on the soil vibration measurements according to the geological conditions of the region. Since the soils present at the site were problematic, and since vibration monitoring studies are site-specific, the present study fills a gap in monitoring data for such sites.

The process of monitoring of vibrations due to pile driving is, in general, well understood. The equipment needs requisite for such monitoring are likewise well established. Consequently, such vibration monitoring related to pile driving has been performed throughout the world [8-10].

Vibration monitoring consists of measuring the ground vibration as a function of the distance from the excitation source. Often these vibrations are compared to applicable code standards.

2. RESEARCH SIGNIFICANCE

The vibration response associated with pile driving will, in general, be affected by the soil profile at a given site. Consequently, the process of vibration monitoring tends to be site-specific. The vibration monitoring study presented and discussed in this paper was carried out for a site in the Republic of Kazakhstan with problematic soil conditions typical of the region. Consequently, the results of this vibration monitoring study will benefit others involved in the installation of deep foundations, especially in close proximity to existing structures, in this region of the world.

3. RESEARCH METHODS

The vibration monitoring study discussed in this paper was performed at five locations at the construction site of the Water Treatment Facility WP1, which is located in the Atyrau Region of Kazakhstan. Figure 1 shows a view of this water treatment facility. In Figure 2, the vibration monitoring locations are denoted by “Location 1” to “Location 5” [11, 12].

The Water Treatment Facility WP1 is part of a rapidly developing water treatment plant, to which new buildings are being added almost yearly. As a result, the distances between buildings are getting progressively smaller. Since deep foundations are required for all of the aforementioned buildings, the effect, on neighboring buildings, of vibrations emanating from pile driving has become a very real concern to the owners of the water treatment plant.

Since buildings and facilities at this site were in rather close proximity to each other, the choice of the five monitoring locations was subject to constraints on available space, etc. Due to the fact that the site had been extensively developed prior to the present vibration monitoring study, soil borings at the five locations were not possible. However, since these locations are in rather close proximity to each other, and due to the fact that the soil profile at this site is relatively uniform, it is safe to assume that variations in the foundation soils did not influence the vibrations measured at the five locations.

Fig.1 View of Water Treatment Facility WP1

The main goal of the present study was to monitor vibrations at different distances from the excitation sources represented by the driving of the three aforementioned piles. In particular, the following details related to the five measurement locations are pertinent:

Location 1 was situated 87 meters away from the pile driving rig during the installation of Pile LTP-1 (Fig. 2). The geophone was fixed to the foundation block of a Turbo compressor. Before monitoring the pile driving vibrations, the device was first used to measure the vibrations emanating from on-site sources (a compressor, grader, excavator and front-end loader).

Location 2 was situated 88 meters away from the pile driving rig during the installation of Pile CTP-1 (Fig. 2). The geophone was mounted to a portion of the foundation (Fig. 3). Prior to measuring the vibrations due to pile driving, it was used to measure the ambient operating vibrations at this location.

Location 3 was situated 75.7 meters away from the pile driving rig during the installation of Pile TTP-1 (Fig. 2). The geophone was again fixed to a portion of the foundation. Prior to measuring the vibrations due to pile driving, it was used to measure the ambient operating vibrations at this location.

Location 4 was situated 89 meters away from the pile driving rig during the installation of Pile TTP-1 (Fig. 2). Similar to Location 3, the geophone was attached to a portion of the foundation. Prior to measuring the vibrations due to pile driving, it was used to measure the ambient operating vibrations at this location.

Location 5 was situated 69 meters away from the pile driving rig during the installation of Pile TTP-1 (Fig. 2). Here too, the geophone was attached to a portion of the foundation. Prior to measuring the vibrations due to pile driving, it was used to measure the ambient operating vibrations at this location.

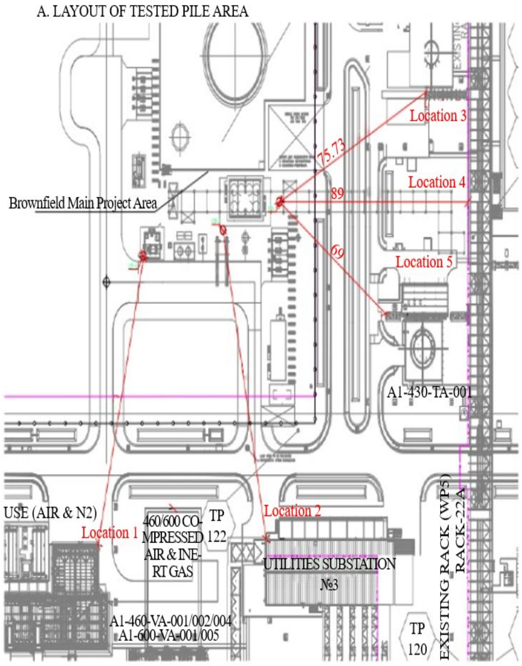

Fig.2 Location of three driven piles and five vibration monitoring locations

For the measurements, five reference points were used, installed at different distances from the pile driving site. In order to assess the effect of vibration on the foundation, it is preferable to select vibration measurement points located directly on the structure and on the side to the vibration source. During the measurements, the actual vibration, frequency, amplitude and acceleration were recorded. Based on the obtained vibration parameters, damping (absorption) coefficients were determined and the maximum permissible pile driving distance was calculated.

The vibrations were primarily generated during the driving of three prefabricated concrete piles at the site. Each of these piles was 12 meters in length and had a square cross-section that measured 40 cm on a side. The decision to use such piles was made independent of the present vibration monitoring study. It is important to note that the results of the preent vibration monitoring study cannot be extrapolated to other types of piles. Instead, a separate such study must be performed for other sites and/or for other types of piles.

The excitation source for the vibrations was a Junttan PM25 pile driving rig, which is shown in the left part of Figure 3. The rig employed a 7-ton hydraulic hammer with a drop height up to 1 meter. The duration of pile driving was between 16 to 17 hours.

At all five of the aforementioned monitoring locations, vibrations were measured using a three-dimensional geophone belonging to the Profound VIBRA+ system that was used in conjunction with a DIN/SBR mounting plate. This equipment is shown in the right part of Figure 3. The vibration velocities were measured in all three (x, y, z) coordinate directions. The x-direction was aligned in the direction of the pile driving rig (i.e., the source of excitation). The z-direction corresponds to the vertical (i.e., the direction of pile driving). Finally, the y-direction is determined form the fact that a right-handed coordinate system is used. All vibration data was recorded using a Profound VIBRA+ data acquisition system, with a measuring interval of 5 seconds. Additional details pertaining to the equipment used in the present vibration monitoring study, including the calibration process for the geophones, are given elsewhere [13].

To minimize any limitations of the vibration monitoring study it was necessary to install sensors on buildings. Associated with this process is the consideration of the following characteristics: type of foundation; structures rigidly adjacent to the foundation; evaluation of bearing capacity structures. Due to the close proximity of the five monitoring locations, and since these locations are near buildings and facilities, the effect of temperature variations on the results obtained will be minor.

Fig.3 Pile driving rig (left) and vibration monitoring equipment (right)

4. RESULTS AND DISCUSSION

The results of the present vibration monitoring study are now presented and discussed.

Figure 4 shows the variation of velocity components as a function of time at Location 1, measured prior to the driving of Pile LTP-1. These velocities are attributed to the ambient operating vibrations emanating from on-site sources such as a compressor, grader, excavator, etc. The maximum velocity components measured for these vibrations were v_x = 0.20, v_y = 0.11 and v_z = 0.26 mm/s. the influence of the on-site vibration sources was thus rather minimal.

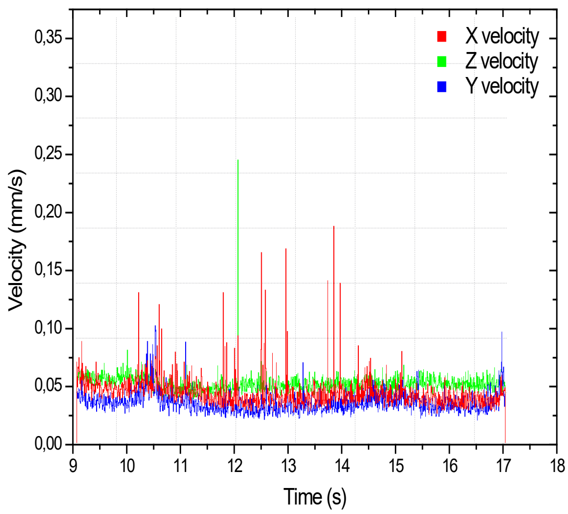

Fig.4 Velocity components as a function of time (in hours) at Location 1 prior to the driving pile LTP-1

Table 1 - Statistical data

Parameter	Locations				
	1	2	3	4	5
Frequency	10	8	10	9	11
Velocity	0.6	0.63	0.65	0.63	1.5

According to the obtained data, all parameters are directly proportional to the distance from the excitation source (Table 1).

Figure 5 shows the aforementioned velocity components as a function of frequency. From this figure, it is evident that there are two primary sources of ambient vibrations, one having a frequency of 0.50 Hz and the other having a frequency of 0.90 Hz.

Figure 6 shows the variation of velocity components as a function of time at Location 1, measured during the driving of Pile LTP-1. The maximum velocity components measured for these vibrations were v_x = 0.31, v_y = 0.30 and v_z = 0.91 mm/s.

Figure 7 shows the aforementioned velocity components as a function of frequency. Although some scatter is evident, the primary frequency associated with the *z*-direction is approximately 10 Hz.

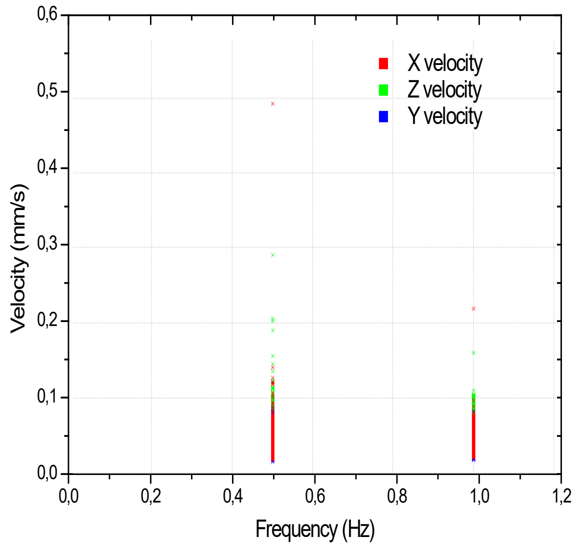

Fig.5 Velocity components as a function of frequency at Location 1 prior to the driving pile LTP-1

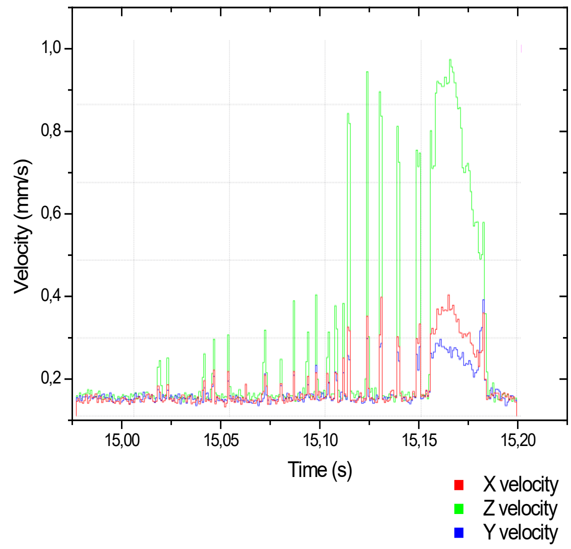

Fig.6 Velocity components as a function of time (in hours) at Location 1 during the driving of pile LTP1

Figure 8 shows the variation of velocity components as a function of time at Location 2, measured during the driving of Pile CTP-1. The maximum velocity components measured for these vibrations were v_x = 0.26, v_y = 0.29, and v_z = 1.19 mm/s. Similar to the results shown in Figure 7 for Location 1, the frequency associated with the *z*-direction is approximately 10 Hz. For this reason, the velocity versus frequency plot for Location 2 is omitted for brevity.

Figure 9 shows the variation of velocity components as a function of time at Location 3, measured during the driving of Pile TTP-1. Compared to velocity–time profiles for Locations 1 and 2, that associated with Location 3 has lower magnitudes and much more uniformity among the velocity components. Indeed, the maximum velocity components measured for these vibrations were v_x = 0.17, v_y = 0.16, and v_z = 0.15 mm/s. From these results, it is evident that the presence of a rather massive foundation located at Location 3 rather significantly reduces the velocity components at this location.

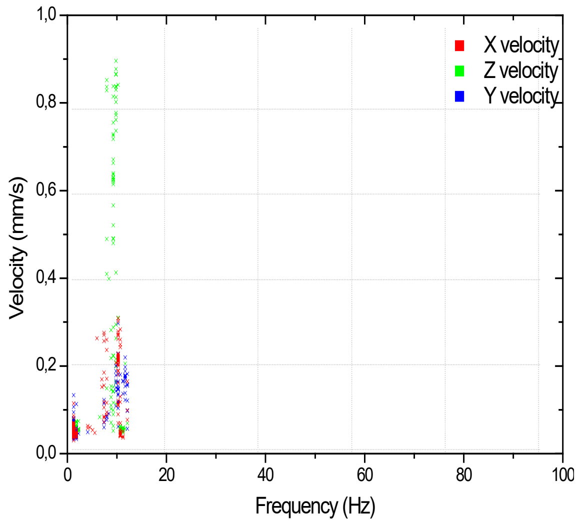

Fig.7 Velocity components as a function of frequency at Location 1 during the driving of pile LTP-1

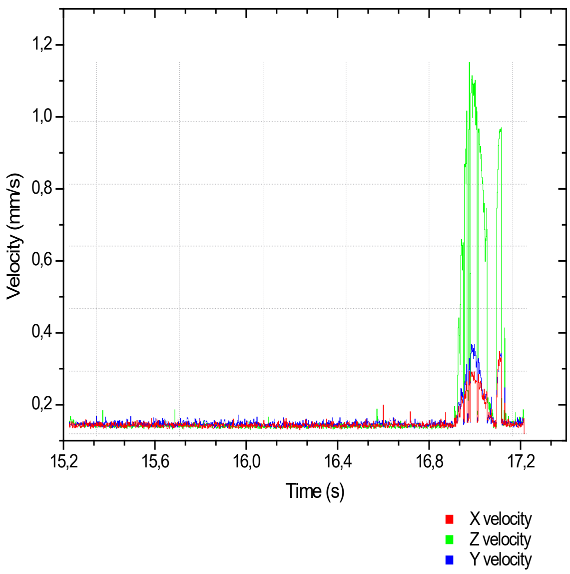

Fig.8 Velocity components as a function of time (in hours) at Location 2 during the driving of pile CTP1

Figure 10 shows the aforementioned velocity components as a function of frequency. Compared to that for Locations 1 and 2 (Fig. 8), the velocity-frequency profile associated with Location 3 shows much greater scatter and a primary frequency in the *x*- and *y*-directions of approximately 7.5 Hz.

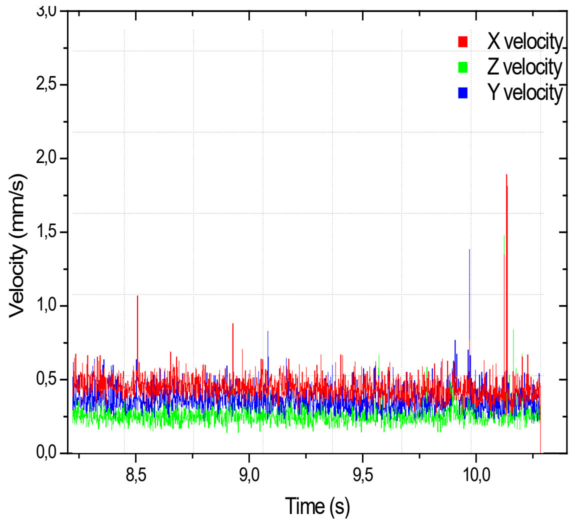

Fig.9 Velocity components as a function of time (in hours) at Location 3 during the driving of pile TTP-1

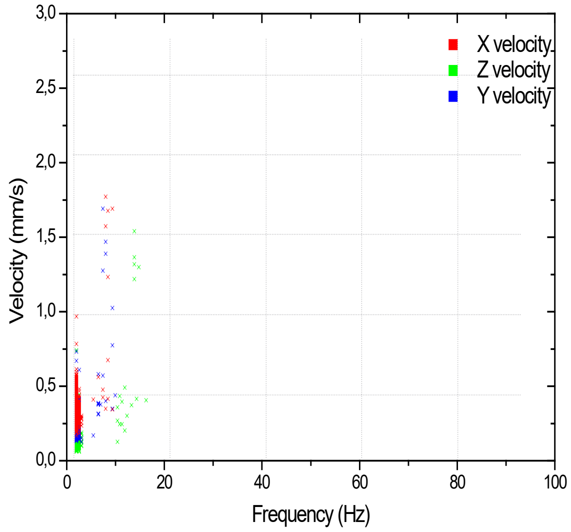

Fig.10 Velocity components as a function of frequency at Location 3 during the driving of pile TTP-1

Figure 11 shows the variation of velocity components as a function of time at Location 4, measured during the driving of Pile TTP-1. The maximum velocity components measured for these vibrations were v_x = 0.35, v_y = 0.64, and v_z = 0.27 mm/s.

Figure 12 shows the aforementioned velocity components as a function of frequency. Similar to Location 3, the velocity-frequency profile associated with Location 4 shows a good deal of scatter. The primary frequencies in the *y*-direction of approximately 10.0 and 17.5 Hz.

Figure 13 shows the variation of velocity components as a function of time at Location 4, measured during the driving of Pile TTP-1. The maximum velocity components measured for these vibrations were v_x = 1.45, v_y = 0.98, and v_z = 1.61 mm/s.

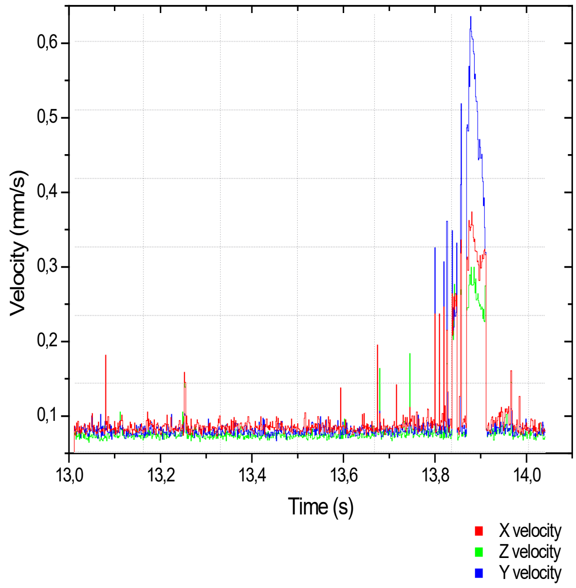

Fig.11 Velocity components as a function of time (in hours) at Location 4 during the driving of pile TTP-1

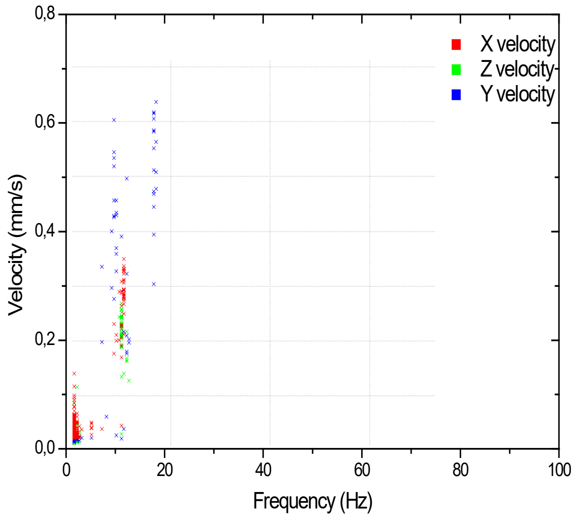

Fig.12 Velocity components as a function of frequency at Location 4 during the driving of pile TTP-1

Figure 14 shows the aforementioned velocity components as a function of frequency. Similar to Locations 3 and 4, the velocity-frequency profile associated with Location 5 shows a good deal of scatter. The primary frequencies in the *x* and *z*-direction of approximately 15.0 and 10.0 Hz, respectively.

Statistical analysis showed that the highest degree of convergence of particular values is observed at the main point, which indicates that the vibration caused by pile driving has the least possible effect on the natural vibrations of the building. In addition, the variability of the ground vibration data at distances of 69 m and 89 m indicates that the vibration caused by pile driving has an effect on the natural vibrations of the ground.

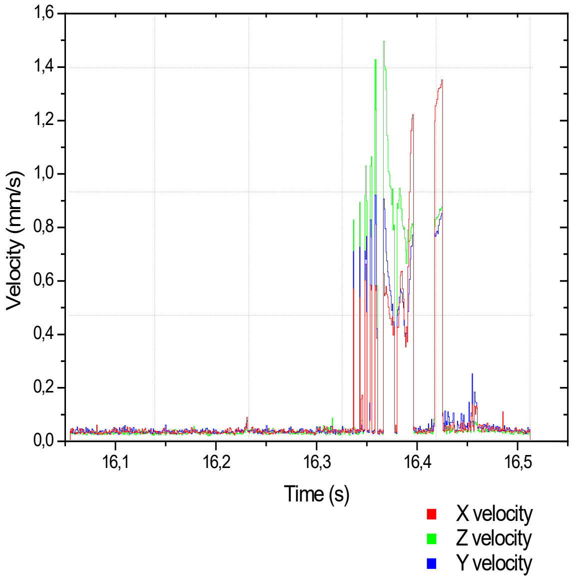

Fig.13 Velocity components as a function of time (in hours) at Location 5 during the driving of pile TTP-1

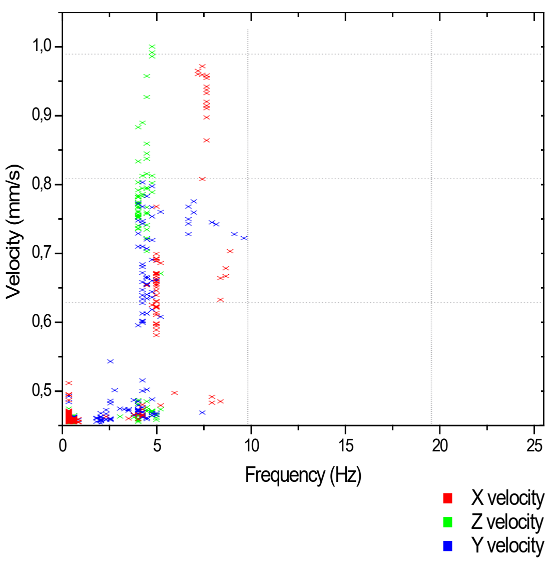

Fig.14 Velocity components as a function of frequency at Location 5 during the driving of pile TTP-1

It is timely to note that, due to the relatively close proximity of the five monitoring locations to each other, the higher frequency vibrations may not have attenuated appreciably. As such, the lower frequency vibrations may thus have been affected. While monitoring locations at greater distances from the pile driving source would have been desirable, such locations were not available within the confines of the Water Treatment Facility WP1.

5. CONCLUSION

This paper presented the results of a vibration monitoring study that was performed at a water treatment facility that was part of a rapidly expanding water treatment plant it a site in the Republic of Kazakhstan. Due to problematic soil conditions, deep foundations are required for all buildings built at this site. Consequently, the effect on neighboring buildings, of vibrations emanating from pile driving has become a very real concern of owners of the water treatment plant.

In the present study, vibrations were monitored at five locations at the water treatment facility. These vibrations were primarily generated during the driving of three prefabricated concrete piles. At all five locations, which were situated at different distances from a particular pile, vibrations were measured using a three-dimensional geophone. The vibration velocities were measured in all three coordinate directions.

The velocities measured at the five aforementioned locations varied in magnitude. The respective magnitudes of the velocity components depended on the foundation conditions at a particular location. In particular, the presence of a rather massive foundation, such as that found at Location 3 in the present vibration study, reduced the magnitudes of the vibration velocities and made the three orthogonal velocity components more nearly equal.

According to the requirements of DIN 4150-3 [13], the maximum permissible vibration speed is 3 mm/s and the maximum vibration frequency is 10 Hz. At no time did the measurements made in the present vibration monitoring study exceed these values. For a given pile, the largest vibration velocities were measured when the 12 meter piles were driven to depths of approximately 5 to 6 meters.

It is important to point out that the above conclusions only apply to the water treatment facility and surrounding treatment plant considered in the present study, with prefabricated concrete piles. These conclusions cannot be applied to other sites. Instead, similar vibration monitoring studies must be performed at these other sites and suitable conclusions drawn from them.

In general, similar to the vibration monitoring of structures [14-20], the monitoring of pile driving represents a robust way in which to quantify potentially detrimental effects on structures. It is thus a useful component in area of structural health monitoring. However, unlike vibration monitoring of structures which quantifies the performance of a finished building or other structure, the vibration monitoring associated with pile driving is employed during the construction process.

The resulting maximum permissible piling distance of 89 m is valid if the piles are driven at the (minimum) distance of 69 m, at which the vibration measurements are made. The driving of piles at closer distances necessitates the re-measuring of the vibration characteristics and, therefore, a possible re-adjustment of the maximum permissible distance, since the ground conditions and vibration propagation near the building may be different.

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