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A Few Considerations about the Property of Ground Vibration Generated by Pile Driving and Its Isolation Methods

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ABSTRACT

This paper presents the results of two field studies conducted on pile driving ground vibration at Toyota Junction on the Second Tomei High-Speed Motorway in Aich prefecture and at a thermal power plant in Chiba prefecture, both of which were under construction. Fathemore, these were compared of a number of different barriers, including open trenches, concrete walls, EPS walls and sheet-pile walls, to isolate ground vibration.

INTRODUCTION

Number of instances is recently on the rise of adverse effects of ground vibration originating in such sources as construction works, machinery in factories, means of transportation including road and railway vehicles. A variety of steps are being taken to isolate houses and other structures from such ground vibration. These include open trenches, underground barriers made of such materials as concrete, expanded poly styrene and urethane, sheet piles, as well as composite barriers built with sheet piles or concrete in combination with expanded poly styrene or urethane.

In this paper, characteristics are described of ground vibration as recorded while steel piles were being driven. Measurements were taken of vibration at two different sites; Toyota junction (Site No.1) on the Second Tomei Motorway and a thermal power plant (Site No.2) in Chiba prefecture, both of which were under construction. At Site No. 1, two types of vibro-pile-driver differing in driving capacity were used to determine how they affected the ground vibration originating in piles being driven. From the results of measurements variation was determined of the level of vibration as a pile penetrated into ground. Effect was identified of the type of pile-driver on the level of vibration and analysis was conducted of the long-distance propagation characteristics of such vibration. At Site No. 2, data were taken of vibration while a steel pile was being driven with a diesel pile hammer. Note should be taken of the fact that in these two studies data were taken over a distance from the source to as far as 100 to 200 m away from it so as to determine the long-distance propagation characteristics of vibration, whereas the distance covered by most of the similar past studies was 30 to 40 m at the longest.

Reference was made to the results of a large number of past studies on steps to reduce ground vibration. Particular attention was paid to those designed to shut off vibration in its path of travel, including open trenches, underground barriers each made of one of such materials as concrete, expanded poly styrene (EPS) and urethane, sheet pile, PC wall piles, as well as composite barriers combining concrete and EPS. Their respective performances were examined with a view to determining the best method for the purpose.

<u>Ground Vibration Arising from Pile Driving</u>

Pile being driven by a vibro pile-driver (Field study No. 1) arrangement for vibration measurement, instruments used

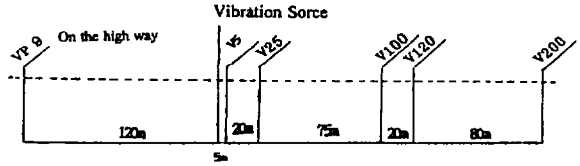

Fig. 1 Arrangement for vibration level measurement

Fig. 1 illustrates the arrangement adopted to measure the level of vibration. Vibration levels were determined of vertical vibration simultaneously at five points on a straight line extending in a given direction from each pile being driven (Line A) and at one point on the same line extending into the opposite direction (Line B).

Six vibration level meters (Type VM-52A, made by Lion) and as many level recorders (Type LR-04, made by Lion) were used for the purpose. The steel piles were all of 800 mm in diameter and consisted of two sections, one 9.5 m long and the other 12 m long , welded together, providing a total length of 21.5m.

Two different types of vibro pile-driver were used to drive the piles; one was electric type (VM2-25000A; 150kW) and the other hydraulic type (PTC100HDRK;451kW). These are shown in Photo 1.

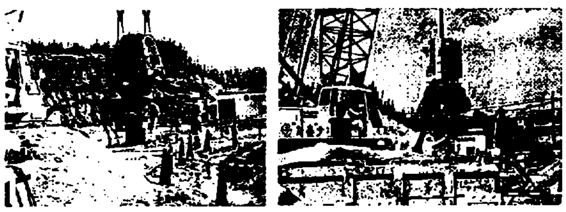

Photo 1 Electric vibro-driver and hydraulic vibro-driver

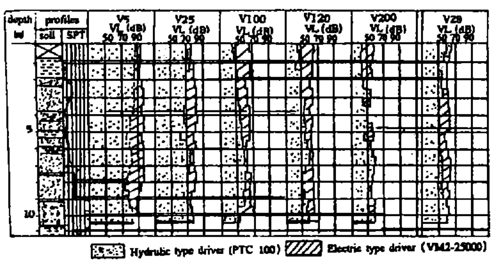

Fig. 2 Boring log and variation of vibration level with pile penetration depth

RESULTS AND THEIR ANALYSES

A boring logs is shown of the soil at the site. From the ground surface to a depth of 13 m, the soil is seen to consist mainly of a silt layer with an intermediate gravel layer being present from a depth of 3.5 m to 6 m. From 17 m and deeper, there is a compact gravel layer with an N-value greater than 50 into which the piles were driven. Ground vibration level was continuously measured while a pile was being driven, and data on the level were read off from the records on the level recorders at 1 m interval as the pile penetrated into the soil.

Variation of Vibration Level with Pile Penetration

Fig. 2 shows how the level of vibration varied as a pile was driven deeper and deeper. No appreciable effect was observed of the type of soil or its N-value on vibration level, no matter which type of the drivers was used to drive a pile. It is generally seen, however, that the level of vibration originating in a pile being driven with the hydraulic driver was lower by about 10 dB at any point within 120 m from it, and was lower by approximately 5dB at any point farther away, than those arising from one being driven with the electric driver.

Propagation Characteristics of Vibration

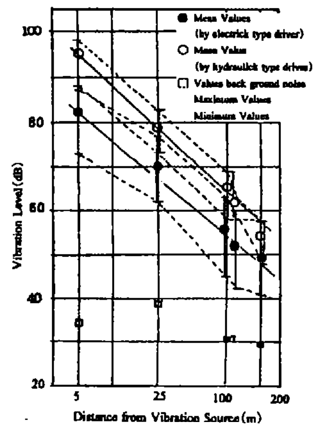

Fig. 3 Vibration Level with the Distance from Vibration Source

Fig 3 illustrates how the level of vibration varied with distance from a pile being driven. The level is generally seen to have decreased with distance at approximately the same rate on average, regardless of the type of driver. The observed rate is approximately equal to the damping gradient of a substantial wave (6 dB/2d, where d is the distance from the vibration source) as reported from past studies. It can further be observed that the level was lower with the hydraulic driver than with the electric type driver. The average level of vibration originating in a pile being driven with the hydraulic type driver was 70 dB at a position 200 m away from it, the farthest point at which measurement was taken, whereas that resulting from a pile being driven with the electric driver was 54 dB. These levels, however, are seen to have been higher than those of average back ground vibration, also shown in the same figure, by about 26 to 30 dB, indicating that ground vibration originating in a pile being driven to capable of travelling quite a long distance.

Vibration Originating in Piles being Driven by a Diesel Hammer (Field Study No. 2)

The sources of vibration herein addressed were steel piles with an outer diameter of 600 mm, a wall thickness of 9 mm and a unit weight of 131 kg/m^3, driven in a grid square pattern, the distance between adjacent piles being 20 m. Of these, totaling 25 in number, measurements were taken of the level of vertical vibration originating in Pile R5 and Pile R10 while they were being driven.

Shown in Fig. 4 is the measuring arrangement. Data were taken at 6 points along each of two mutually perpendicular lines (Line A and Line B) intersecting at the centre of a given pile, and by using the same instruments as those used for the field study No. 1.

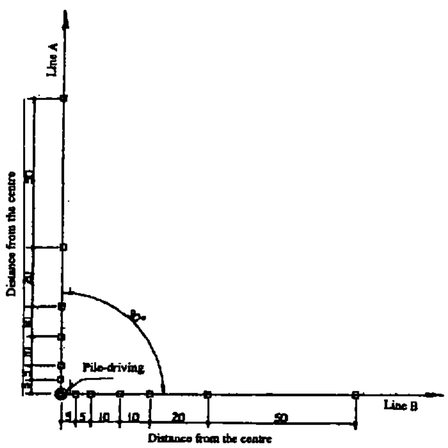

Fig. 4 Arrangement for vibration level measurement

Fig. 5 shows the boring log taken at the site. The soil is seen to contain a land fill layer to a depth of 6.5 m having an N-value between 4 and 15. From there to a depth of 20 m, there is another layer consisting of fine sand or fine sand mixed with silt whose N-value varies from 35 to over 50. Thus, the soil being addressed can be assumed to be composed of two distinct layers.

Vibration Level and Pile Penetration Depth

Shown respectively in Figs 6-1 and 6-2 are the variation in vibration level as recorded while Pile R5 and Pile R10 were driven deeper and deeper. It can be noted that :

(1) There is a difference of about 6 dB between the level recorded on Line A and that on Line B, both at a distance of 100 m of the vibration originating in Pile R5,

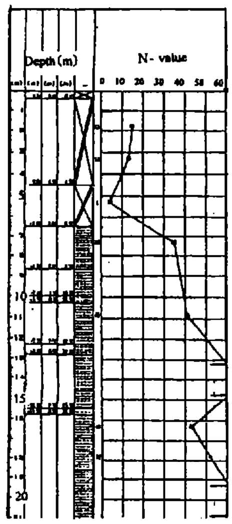

Fig. 5 Boring Log and Soil Property (Field study No.2)

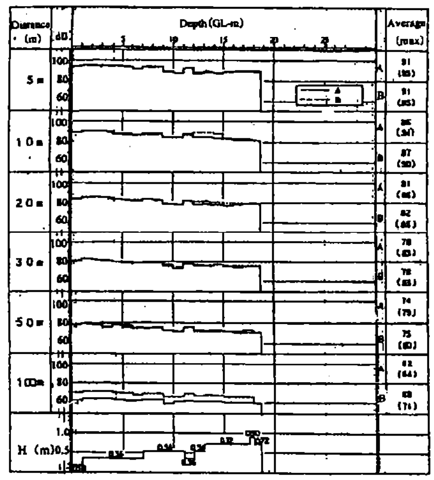

Fig. 6-1 Level of Vibration and Depth of Pile Penetration (Pile R5)

(2) With respect to the vibration originating in Pile R10 as recorded at a distance of 10 m from it, the level on Line A differed by about 10 dB from that on Line B. This may have arisen from the possible difference in the conditions of ground surfaces on which respective pick-ups were set up.

(3) An increment was recorded in the level of vibration as the piles went through the fine sand layers existing at a depth of 7 m and from 11 to 12 m. This increment is consistent with the variation in N-value of the soil with depth.

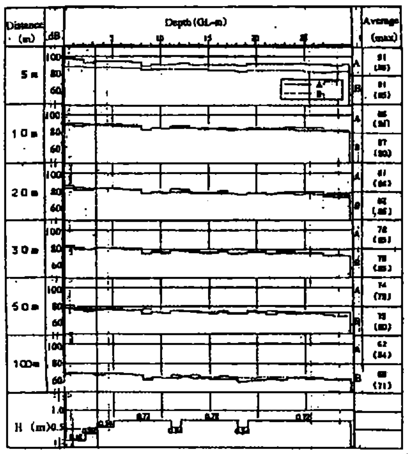

Fig. 6-2 Level of vibration and depth of pile penetration (Pile R10)

Propagation Characteristics of Vibration

Shown in Fig. 7 are the mean and maximum levels of ground vibration recorded at various points on Line A and Line B as each of the piles was driven deeper and deeper. The mean level was determined by averaging those recorded at every 1 m of pile penetration.

The levels are seen to have decreased approximately linearly at a rate of -6dB/2d, this rate being consistent with the damping characteristic of a body waves as was observed with the vibration originating in a pile driven by either of the vibro pile-drivers. The vibration is seen to have been capable of travelling quite a long distance without losing its intensity, the level of about 62 to 68 dB recorded at 100 m away from the source being well over the limit of human sensitivity (60 dB).

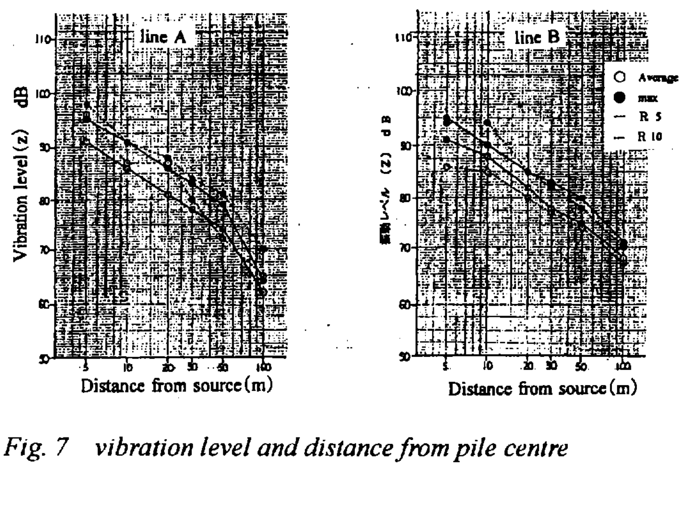

Fig. 7 vibration level and distance from pile centre

Empirical Propagation Characteristics

Relative levels were determined of ground vibration, each being the difference between the average value registered at a given point and that recorded at a point 5 m away from the source. Data taken through both study 1 and study 2 were used for the purpose. The results are plotted in Fig. 8, showing how such relative level decreased with distance. This decrease can be represented, in an approximate manner, by an empirical formula proposed by G. Bornitz [1931]

$$L_{vr} = L_{vr0} - 20\log(r/r_0)^n - 8.68\,\alpha\,(r/r_0) \qquad (1)$$

Where; L_{vr} : Vibration level at a given point (dB)
L_{vr0}: Vibration level at a reference point (dB)
r : Distance between source and a given point (m)
r_0 : Distance between source and the reference point (cm)
α : Coefficient of internal damping
n : Coefficient of geometric damping
$n = 0.5$ for surface wave
$n = 0.75$ for substantial combined wave
$n = 1.0$ for substantial body wave

Assuming that the propagating wave of a vibration arising from a pile being driven comprises a body waves as well as a surface wave, n can be taken for 0.75 and α for 0.01, this latter being the coefficient of internal damping of a soil composed of sand and gravel.

A specific empirical equation was worked out by substituting these into the general formula. The equation, represented by a solid line in Fig. 8, is seen to be in good agreement with the measured data. It can therefore be assumed that the vibration originating in a pile being driven travels as a compound wave combining a substantial wave and a surface wave to a distance as far away as 100 to 200 m from the vibration source.

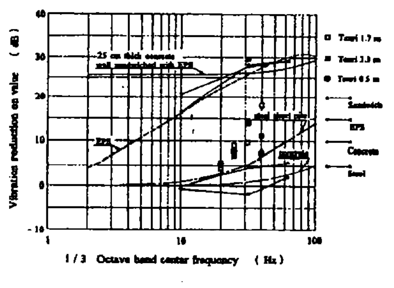

Fig. 8 Reduction in vibration level with distance

COMPARISON OF EFFECTS OF VIBRATION ISOLATION THEORETICAL PERFORMANCES

Fig. 9 shows the performances, estimated by using a widely applied wave penetration theory, of four different underground barriers. These are three simple barriers, each made of a single material; concrete, expanded poly styrene (EPS) and steel sheet-piles, and a composite barrier consisting of 50 cm-thick EPS sandwitched between two 25 cm-thick concrete walls.

For the purpose of comparison, effects were calculated of the barriers assuming that they were infinitely deep and long, and 10 cm in thickness. Additionally, vibration waves were assumed to travel at a speed of 300 m/s through the soil, the speed at which such a wave normally propagates though a fairly compact soil, with a view to comparing the performances with those from another study previously conducted by one of the authors at a site in Tenri. The data taken there are also plotted in Fig. 9. The barriers tested there were two open trenches, one 1.7 m and the other 3.3 m in width, and a composite barrier consisting of a 50 cm-thick ESP sandwitched between two concrete walls, both being 25 cm in thickness.

The results of calculations using the wave penetration theory indicated that the composite barrier was highly effective to isolate around vibration even at a lower range of frequency. Among the barriers composed of a single material, the ESP wall is seen to provide the best performance, that built with steel sheet-piles the second followed by the concrete wall. It can also be appreciated that the smaller the impedance ratio against wave propagation (density x speed at which S wave travels), the wider the range of frequency over which a barrier is effective. The barrier made of steel sheet-piles is seen to reduce vibration level by about 5 dB in theory. In practice, however, a barrier as thick as 1m could not possibly be built with available steel sheet-piles.

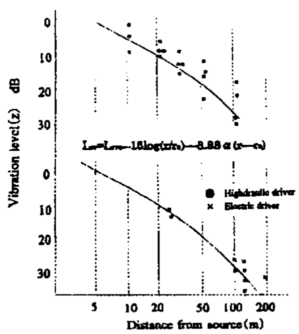

Fig. 9 Theoretical performances of different barriers

data from past studies

Data have been reported elsewhere on the performances of different types of barrier including open trenches, and those made of EPS, concrete, PC wall piles and steel sheet-piles in terms of reduction in vibration level. The reduction herein referred to is the difference in vibration level as recorded at a given position without a barrier and with a given barrier. These data were collated as appropriate and plotted in Fig. 10 against distance from a given barrier for comparison. The thin solid lines represent the linear relationships determined by using an iteration method to fit a given set of data as measured through a particular experiment, while the thick ones those worked out with the same method to fit all the available data as measured on a given type of barriers.

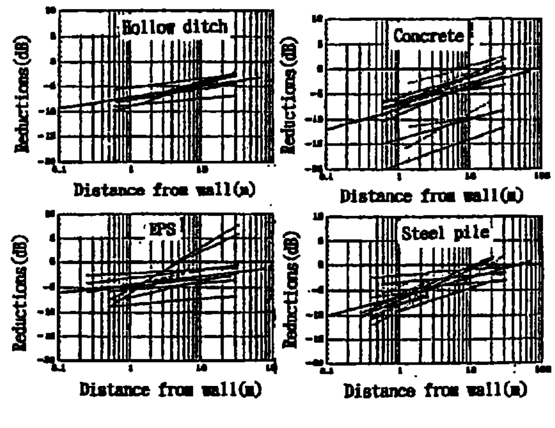

Fig. 10 Performances of different barriers as measured (in terms of reduction in vibration level)

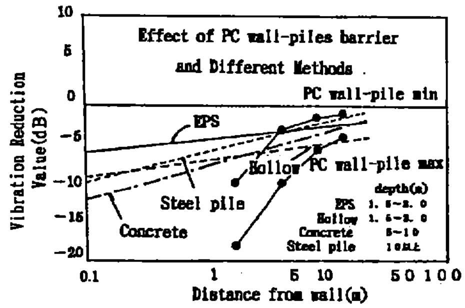

Fig. 11 Performances of different types of barrier

From the data shown in Fig. 11, it can be seen that the steel sheet-pile barriers are capable of reducing vibration level over a distance of about 45 m, and those made of concrete are effective to as far as 90 m. The open trenches and ESP barriers in their turn are seen to be effective up to a distance as long as 100 m and beyond. It is also seen that when it comes to the reduction in vibration level just behind the barrier, the PC wall-pile barriers provide the best performance, concrete barriers the second, steel sheet-piles barriers the third, followed by open trenches, and ESP barriers in this order. The open trenches and ESP barriers, however, are seen to provide a higher performance than the others as the distance increases. It can thus be assumed that, although capable of reducing the level of vibration at high frequencies because of their higher impedance against wave propagation than that of soils, the concrete and steel sheet-pile barriers may not be as effective as the others at lower frequencies. The open trenches, which should have provided the best performance, are seen to have been less effective than the concrete and steel sheet-pile barriers. The reason for this may be that their depths, and the composition of soil there, might have had larger effects than their materials. The open trenches and EPS barriers herein addressed, were not as effective as the others possibly because, built to a depth of only 1.5 to 2.0 m, were not capable of shutting off vibration waves reflecting from the interfaces between various soil layers as well as those due to refraction from below their bases, whereas the concrete and steel sheet-pile barriers, have proved more effective than the former, possibly because they were much deeper (from 5 to 10 m), and thus capable of isolating such waves.

CONCLUSIONS

With a view to investigating adverse effects of ground vibration arising from construction works, a series of studies were conducted on the level and long distance propagation of ground vibration originating in steel piles being driven with an electric and hydraulic hydraulic type vibro-drivers, as well as a Delmack type diesel hammer. By using the data taken, and also based on a wave penetration theory, performance was examined of each of a number of different barriers currently employed to isolate such vibration. Conclusions were drawn as follows:

1) No appreciable effect was observed of the property of soil or its N-value, or the depth to which piles had been driven, on the level of ground vibration all over the distance addressed, regardless of the type of driver,
2) The level of ground vibration originating in a pile being driven by a hydraulic pile driver was found to be generally lower than that generated by a pile being driven by an pile electric driver, the former being lower than the latter by about 10 dB over a range from vibration source to 120 m from the pile, and by approximately 5 dB beyond that range,
3) The rate at which the level of vibration decreases with distance was found to be approximately consistent with the damping characteristics of a vibration wave combining body and surface waves, regardless of the type of pile driver,
4) The level of vibration recorded at 100 m away from a pile being driven by a diesel hammer was from 62 to 68 dB, while those registered at 200 m away from piles being driven by an electric and hydraulic vibro pile-hammers were 54 dB and 50 dB respectively, indicating that such vibration is capable of travelling quite a long distance,
5) Through an analysis based on a wave penetration theory, composite barriers were recognised to be highly effective to shut off ground vibration, even at a lower range of frequency. Of those made of a single material, the EPS barrier was found to be the most effective one, followed by the steel sheet-pile barrier and concrete barrier in this order, indicating that the lower the wave impedance of the material, the more effective a barrier become,
6) The effective distance can be assumed to be about 45 m for a steel sheet-pile barrier, approximately 90 m for a concrete barrier, and over 100 m for an open trench and EPS barrier,
7) Among those tested, PC pile barriers proved to be the first, concrete barriers the second, followed by steel sheet-pile and EPS barriers, in the order of effectiveness as determined just behind them. At points farther away, however, open trenches and ESP barriers were found to provide better performances than the others.

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