REVIEW OF IMPACT OF VIBRATION TECHNIQUES ON FLOOD DEFENCE STRUCTURES (FDS)

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1 INTRODUCTION

Flood defence structures (FDS) are engineered solutions to prevent and/or mitigate the impact of flooding from water courses or deposits and in the UK are erected and maintained by the Environment Agency (EA).

The EA defines FDS assets as "any natural or man-made structure or feature, such as walls, buildings, earth embankments, shingle banks, or raised areas of land". This paper is part of a report commissioned by the Department for Environment, Food & Rural Affairs (Defra) for use by all those involved in planning and development in the vicinity of flood defences, and in particular the EA, that seek to provide guidance and vibration assessment upon hard flood defences built on foundations and with stone wall elements, or in a gabion configuration.

One typical construction activity that occurs near to FDS and generates vibration is piling. These operations result in groundborne vibrations during the driving of the pile into the ground. Vibratory waves originate from the pile driver, with properties depending on the method used, and are transmitted and radiated through the pile shaft and pile toe. The waves propagate through the terrain and can transfer into other structures under or above the ground. Such vibration can cause damage to structures either directly as a result of dynamic effects like the motion in the structure generated by the vibrations or by other causes of damage such as soil settlement, differential settlements, heaves and ground distortions.

At the time of this document there is a lack of a robust assessment methodology to determine the effects of vibration arising from piling techniques on the stability and integrity of FDS and there is no general agreement on safe limits to avoid damage to the FDS.

This paper includes a summary of piling techniques available, existing vibration limit criteria, vibration metrics used and vibration prediction models for different piling techniques. The objective is to avoid the impact of vibration arising from piling upon FDS, including ground distortions and settlements.

2 LITERATURE GAPS

The main identified gap in the literature reviewed is the lack of vibration data directly measured near or on flood defences as a result of piling operations. The majority of the field studies provide data in the vicinity of piling operations or in residential buildings. In most cases, the footings of walls for flood defences may not be directly comparable to those for residential buildings as they are designed to support different loadings. Assessment of the potential damage is therefore based on partial similarities in the foundations.

Another identified gap in the literature reviewed is the lack of extensive research on ground distortion and settlements caused by vibration. There are different approaches to assess the likelihood of settlements as a result of vibration, but field data is not extensively available.

3 HIERARCHY OF PILING TECHNIQUES

Impact and vibratory piling are the most prominent sources of vibration of all the piling techniques available and are widely used in the UK. With impact pile driving techniques the frequency content of ground vibrations cannot be controlled by changing the pile driving process, which is the case in vibratory piling as the frequency of operation of the vibratory pack can be adjusted[22]. Vibratory piling is used mainly for driving and extracting sheet piles[10]. This technique is not commonly used for pre-cast concrete piles or H-shape steel pipes due to the lack of guidelines in relation to driving to refusal[27].

Other piling methods that are likely to generate less groundborne vibration include rotary bored piling, continuous flight auger (CFA) piling and press-in piling, with this last technique sometimes classified by manufacturers as noise and vibration free.

Below is presented a hierarchy of piling techniques in terms of expected levels of vibration generated.

- Press-in piling (Likely to generate minimum vibration).
- Rotary Bored piles / CFA piling (Likely to generate less vibration).
- Vibratory piling / Impact piling (Likely to generate more vibration).

4 PROPAGATION OF VIBRATION, GEOLOGICAL CONDITIONS

The geological conditions affect groundborne vibration propagation, with higher levels of ground vibration as a result of impact pile driving usually found in stiff, dense soils more than in loose soft soils.

Head & Jardine (1992)[12] and Deckner (2013)[10] concluded that the main factor contributing to vibration was the resistance of the soil to the pile being driven. With an increased resistance, the necessity of applying greater energy during the driving process makes it more available to be transferred to the soil.

Hiller and Crabb (2000)[14] Compiled results of various researchers regarding the correlation between ground vibrations and soil resistance, pointing out that more vibration was dissipated as elastic waves in soils that offered more resistance to the pile to be driven, such as stiff or dense soils.

Stiff soils like stiff clayey soils, consolidated sand, gravel and glacial till propagate vibration more in the far field but appear to display lower vibration amplitudes in the near field. Soft soils, such as clay, loam and silt attenuate the propagation of vibration more in the far field but display higher vibration amplitudes in the near field[4].

Impact piling displays higher vibration levels in stiff soils than soft soils. Higher-frequency vibrations attenuate faster than lower-frequency vibrations, and it appears that impact piling exhibits higher frequency vibration than vibratory piling. In general, impact piling presents more energy across the frequency spectrum. With regards to impact piling, different types of hammers (drop, diesel and pneumatic) tend to produce similar levels of vibration. Impact piling involving concrete piles tends to generate more vibration than impact piling involving steel piles [3,10].

5 VIBRATION LIMITS

Damage caused to structures from groundborne vibrations can occur as a result of dynamic stress or due to settlements and partial settlements.

Standards and technical documents presenting vibration limit criteria to prevent damage in buildings or structures are derived from research conducted for blasting operations and, in the absence of specific criteria, have been widely used for the assessment of vibration impact upon structures for other construction activities such as piling.

However, it has been acknowledged that the nature and composition of vibration events caused by blasting operations do not represent or correlate well with vibration events caused by pile driving operations. During blasting operations, the amplitude of the vibrations can be higher, but the total number of cycles is usually much less than during piling [10]. It was determined that cycles of ground vibrations during piling could be a thousand times higher than during blasting[18].

The duration of the vibration event is an important factor for building damage. Motion of short duration might not be able to produce enough load reversals for damaging response to build up in a structure even with high amplitudes. However, motion with moderate amplitudes but long duration can produce enough load reversals to cause substantial damage[17,23].

In impact piling, with vibration durations between 0.2-0.3s, resonance build-up of structures is unlikely. The importance of frequency content is more important in vibratory piling regarding potential resonance in structures[26,29].

The vibration velocity appears to correlate well with impact on structures and is the most widely used indicator in guidance documents and standards when presenting vibration limit criteria to prevent damage to buildings and structures. However, for clarity it should be noted that it is the dynamic strains caused by vibration, rather than the velocity of the vibration itself, that result in structural damage.

Most vibration standards relate to blasting activities and the dynamic characteristics of blasting vibration can be significantly different to those from pile driving. Another limitation of existing standards is the lack of consideration of geotechnical problems like the geological conditions of the terrain and the type and material of structures and foundation. These factors are important when assessing the risk of damage caused by vibrations. Another important aspect usually not considered is the potential settlements and partial settlements in non cohesive soils caused by groundborne vibrations, which are not directly related to dynamic effects and have been already acknowledged as a potential risk for the integrity of structures[22].

The Swedish Standard SS-025211 (Svenska institutet för standarder [Swedish Institute for Standards], 1999)[24] appears to be the most comprehensive and detailed document when determining safe vibration limits from piling operations, as it considers important aspects such as geological conditions and building foundation parameters. The method presented is based on extensive research and measurement exercises undertaken during piling operations and observations of the damage caused by piling in Sweden and accounting for the geological conditions in that country. The types of soils presented in this document are generalised to 4 different types and these are also found in the UK.

This document presents the following equation to determine a suitable vibration limit criteria and provides tabulated values for the different factors:

$$\mathrm{PPV} = V_0 * F_b * F_m * F_g$$

- V_0: Uncorrected vibration velocity in mm/s.
- F_b: Building factor. Depending on the type of building/structure
- F_m: Material Factor. Depending on the type of material of the structure/foundations
- F_g: Foundation Factor. Depending on the type of foundations
- PPV: Peak value of the vertical vibration velocity in mm/s(measured on bearing elements of the building foundation)

The calculated levels do not take into consideration the effects of vibration on occupants of the building. vibration limit criteria are not frequency-dependant because the dominant frequency of vibrations measured during piling operations usually varies within a narrow range.

Considerations should also be given to the vibration limit criteria presented in BS 5228-2[6] and BS 7385-2[7] as these have been widely used in the UK but considering that they are limited and derived from blasting operations rather than piling operations.

6 GROUND SETTLEMENTS

The effects of pile driving vibrations in densifying cohesionless soils may be much more significant to adjacent structures than any vibrations transmitted directly to those structures[13].

Bement & Selby (1997)[5] showed that loose granular saturated soils may compact during prolonged vibration if the particle acceleration exceeds 0.2-0.4g, with a rapid increase in settlement with particle acceleration above 1g. Settlements appear to be limited to depths of 10 m under the surface and at distances in excess of 5 m from the piling location, compaction is not likely to occur unless liquefaction effects are present on site.

Vibration measurements from impact piling operations indicated vibration levels up to 0.4g immediately adjacent to the piles and a rapid attenuation over distance, with attenuation rates depending on the geological conditions. Acceleration values at 30m from the piles were 0.03g. Settlements were most significant near the piles and in the loose fill deposits. Settlements of 15 cm and greater were observed next to the piles, but these decreased and practically were not present at distances over 12 m from the piling location. Typically only minimal settlements were observed until acceleration levels exceeded 0.05 g[8].

Massarsch (2004; 2000)[19,20] indicated that the magnitude of settlement depends primarily on the shear strain and the number of vibration cycles. The conclusions obtained indicate that frequency and ground acceleration are negligible when assessing potential settlements. Shear strain and number of vibration cycles are more useful parameters. The shear strain is the primary factor causing compaction of granular material and that compaction increases with shear strain amplitude. Vibration levels generating shear strain levels of 0.01%, are likely to result in ground distortion and settlement and shear strain levels exceeding 0.1% indicate a significant risk of settlements.

There are no clear criteria for safe limits for ground movement/settlement due to pile driving that an adjacent structure can tolerate. Criteria in terms of the shear strain, provide a useful and quantifiable method to estimate the likelihood of soil settlement in non-cohesive soils. Field data indicates that compaction occurred in loose to medium-loose granular soil when measured Peak Particle Velocity (PPV) levels at ground surface ranged between 2.5-5mm/s [10].

The Hong Kong Note APP-137 (Government of the Hong Kong Special Administrative Region, 2018) establishes vibration limit criteria in terms of displacement, with minimum displacement warning levels of 12mm to avoid total settlement. Although the note does not specify the definition of total settlement, it is understood as the settlement (change in vertical distance of the surface level) of the total ground area occupied by the structure, in opposition to differential settlement in which only a portion of the ground area is subjected to settlement.

7 PREDICTION MODELS

7.1 Empirical Models

Hope & Hiller (2000)[15] concluded that although the potential energy of the hammer is a good starting point to estimate the energy transferred to the ground from the pile, they observed that there was no linear relationship between the potential energy of the hammer and the measured vibration in terms of PPV. They indicated that the groundborne vibration varies significantly depending on the soil type and the depth of the penetration. They stated that a predictor that does not take into account soil type cannot yield accurate predictions of groundborne vibrations from piling operations.

The majority of adopted prediction methods are empirical equations that have been developed based on measured data and extensive data collection exercises. Most of the empirical methods currently available for impact piling vibration rely on the term $\sqrt{\boldsymbol{W_r}}/\boldsymbol{D}$, (where D is the distance between the pile and the receptor and Wr is the rated energy of the piling driver) which results in a normalised or scaled distance/energy, based on the distance between source and receiver and the square root of the rated energy of the piling driver used. This term is useful to compare piling generated by mechanical plant with different energy ratings. Early empirical methods based on the normalised distance/energy also included a constant of proportionality and a coefficient for geometric damping but did not account for soil types and the associated propagation attenuation.

Attewell and Farmer (1973)[2] developed one the first empirical methods to estimate vibration levels due to impact piling based on the scaled distance method and the square root of the energy supplied by the hammer.

Hiller and Crabb (2000)[14] presented an empirical model for impact pile based on the scaled energy approach and square root energy dependency and an empirical model for vibratory piling based on a best-fit curve developed from an extensive data collection exercise. These two empirical models for impact and vibratory are the proposed prediction models presented in the current version of BS 5228-2:2009+A1:2014 Code of Practice for noise and vibration control on construction and open sites – Vibration[6].

Whyley and Sarsby (1992)[28], among other researchers, also further developed the empirical model to predict vibration from impact piling based on the scaled distance to account for geological conditions which was determined to be critical to obtain more reliable predictions.

Grizi, Athanasopoulos-Zekkos and Woods (2018)[11] carried out a study to determine vibration attenuation in the near and far field. The conclusion obtained was that correlations between measured data and empirical models are valuable but can underestimate or overestimate the expected ground vibrations. The Bornitz equation appeared to present a satisfactory correlation for sand and clay soils, and it is recommended as a preliminary evaluation of vibration induced by piling operations. However, it acknowledges that reflection and refractions caused by the different layers of soils affect the wave attenuation and are not covered by the Bornitz equation. The study recommends field data collection for critical projects to verify predictions.

7.2 Theoretical Models

Davis (2010)[9] listed numerical methods that can be used to construct prediction models:

- Finite Difference Time-Domain Method (FDTD or FDM): These methods are essentially numerical solutions of the wave equation.
- Finite Element Method (FEM): Commercial software available such as COMSOL and PLAXIS.
- Boundary Element Method (BEM): These methods essentially solve partial differential equations.

7.3 Engineering Models

These models are a combination of different approaches. Jongmans (1996)[16] states that vibration amplitudes, durations and waveforms are strongly dependent on the source characteristics and the geometry and geological conditions of the terrain, and how it is unlikely to obtain accurate vibration levels without knowing the main features of the site. Jongmans proposes using classical seismic tests to determine the geometry and dynamic characteristics of the geological layers, assumed to be horizontally layered, then proposes a method for a propagating function of the site between the pile toe and soil using Green's function. Jongmans acknowledges that this method is limited and dependent on the creation of databases to allow for use on different sites.

Svinkin (1996)[25] introduces an engineering model based on the application of a deterministic impulse response function to tackle the geotechnical problems of predicting ground and structure vibrations before the installation of the vibration source. The impulse responses are determined experimentally for every considered dynamic system and reflect the real behaviour of the soil and structure without investigating the soil and the structure properties. With the impulse response function determined, the dynamic loads for the pile driving are computed with wave equation analysis and then Duhamel's integral is used to predict vibrations.

Massarch and Fellenius (2008)[21] introduced a theoretical concept with a simplified model that considers the strain softening effect on the wave velocity in the soil. The researchers indicate that is possible to calculate the attenuation of spherical and surface waves and of cylindrical waves generated at the pile toe and the pile shaft. The model uses the force that is applied to the pile, the dynamic stress in the pile and the dynamic resistance along the pile toe and pile shaft.

8 VIBRATION MONITORING

Due to the current limitations to obtain accurate and reliable vibration prediction from piling operations, vibration measurements may be necessary to verify the predicted values and ensure the integrity of the flood defences.

If the flood defences are located at a considerable distance from the piling operations and a competent person has deemed the vibration contribution negligible or comfortable below the adopted vibration criteria, measurements may not be necessary. The competent person would need to ensure that the predicted levels are consistent considering all the variables in terms of geological conditions, piling locations and potential progression of the works and relocation, as well as all the FDS locations.

If the flood defences are located at a distance where vibration levels are predicted to be below the adopted vibration criteria but with uncertainties regarding potential exceedances, short-term measurements of representative piling operations are recommended to determine the vibration levels received by the piling operations. This can be done as part of trials before the starting of the works or during the works programme, with regularly scheduled surveys depending on the progression of the works.

9 CONCLUSIONS

The piling technique considered to generate less groundborne vibration is press-in piling followed by rotary bored piles and CFA piling, with vibratory and impact piling likely to generate more vibration.

Stiff soils propagate vibration more in the far field and display lower vibration amplitudes in the near field. Soft soils attenuate the propagation of vibration more in the far field but display higher vibration amplitudes in the near field. Vibratory piling seems to generally exhibit a lower frequency component than impact piling. In terms of energy amplitude, impact piling presents more energy across the frequency spectrum.

Vibrations with a high frequency component are attenuated faster over distance than vibrations with a low frequency component.

For flood defence systems based on concrete foundations or with engineered walls, it is recommended that the vibration limit criteria be determined taking into consideration the method proposed in SS-025211 as it considers geological conditions, foundation types and has been derived from piling operations rather than blasting operations. It is acknowledged that vibration limit criteria presented in BS 5228-2[6] and BS 7385-2[7] have been widely used in the UK but it is important to understand the limitation when using it to assess vibration from piling operations.

If unknown, it is recommended to undertake a study of the ground conditions to establish the type of soil in the piling site. If the soil type is non-cohesive and the flood defences are located within 5m of the piling location it is recommended to undertake a more in-depth study to estimate the potential shear strain generated and compare and assess it with the limits proposed by Massarch (2004)[20]. Based on the data presented above and the observed compaction in loose to medium soils with measured vibration levels between 2.5-5mm/s, suggested maximum PPV levels below the lower limit (measured on the ground surface) might be suitable to initially control settlements in immediately adjacent areas to the piling.

Empirical models are indicated as the better option in terms of practicality for practitioners rather than theoretical and engineering models to obtain vibration predictions. Based on the available literature it appears that empirical models can under- or overestimate vibration levels resulting from piling operations, but in the absence of more practical models they still remain the most useful tool for estimating vibration levels due to their simplicity and little amount of input data required. Researchers concluded that models that do not take geological conditions into account are not reliable and not capable of yielding trustworthy results.

It is therefore recommended to use a combination of tools to overcome the limitations and reduce the uncertainties of using only one approach. The empirical models based on the scaled energy approach and the Bornitz equation appear to be one of best available methods to estimate vibration levels currently.

Hiller & Crabb (2000)[14] and Whyley & Sarsby (1992)[28], among other researchers, further developed the empirical model to predict vibration from impact piling based on the scaled distance to account for geological conditions which was determined to be critical to obtain more reliable predictions. For the prediction of vibration from vibratory piling it is recommended to use the model proposed by Hiller and Crabb (2000) based on a Best-Fit curve.

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