Rock Music Induced Damage and Vibration at Nya Ullevi Stadium

A. Bodare
Royal Institute of Technology, Stockholm, Sweden

S. Erlingsson
Royal Institute of Technology, Stockholm, Sweden

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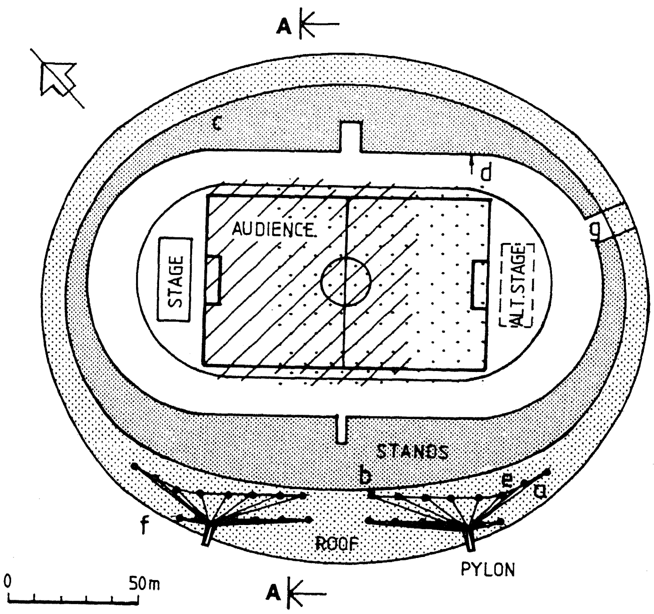
A. Bodare
Assistant Professor, Department of Soil and Rock Mechanics, Royal Institute of Technology, Stockholm, Sweden

S. Erlingsson
Research Engineer, Department of Soil and Rock Mechanics, Royal Institute of Technology, Stockholm, Sweden

;YNOPSIS Two rock concerts were held in the City of Gothenburg, Sweden at Nya Ullevi soccer stadium the summer of 985. The stadium is founded on driven piles in soft clay. An enthusiastic audience was jumping in time to the songs. Violent ibrations of the suspension wires and in the cantilever roof beams of the structure were observed and damage to the roof and he building itself was detected after the concerts. People on the pitch and inside the stadium building experienced excessive ibrations. Residential buildings 400 m away experienced vibrations. Concerts are at present not permitted at the stadium. The Gothenburg community suffers financially as a result of being unable to arrange concerts such as these. The high vibration level which occurred during some of the songs can be explained by resonance phenomena in the clay deposit. The paper describes the amage to the structure, the experience of people inside and outside the stadium and by the use of calculations arrives at an xplanation for the excessive vibrations.

NTRODUCTION

n the summer of 1985 rock artist Bruce Springsteen and his and gave two concerts in Nya Ullevi Stadium, Gothenburg, Sweden. An audience of approximately sixty thousand eople was present. A good half of the audience was in the tands on both long sides and on the south east short side. The rest, more than twenty-five thousand people were tanding on the field, most of them just in front of the stage. See fig. 1.



g. 1. Plan of Nya Ullevi Stadium. Points indicated by lower se letters are explained in the text.

During those songs with a more driving beat the audience jumped in time to the music. In this way the audience on the pitch excited the clay layer from the surface, with the same frequency as the beat of the music. These songs can last for several minutes and can easily cause a build up of a high vibrational level (Pernica, 1982). Sahlin (1987) investigated the load-time function of music such as this and found that the frequency was close to 2.4 Hz. This means that during one particular song of approximately four minutes duration the number of loading cycles is more than five hundred. For this reason practically the whole deposit under the stadium started to vibrate, leading through the structure base and pile system to vibrations in the structure as a whole. Vibrations in the building and roof during these songs became very powerful. Indeed members of the public even moved to seek safer locations elsewhere. Damage was afterwards discovered. This led to a prohibition of further rock music concerts in the stadium.

Nya Ullevi is Swedens biggest athletic arena. It was built in 1958 for the final stages of the soccer World Cup. It hosted the final stages of the European Nations Cup in soccer last year and in 1995 the World Athletics Championships will take place there. It was, however never designed for dynamic loads, apart that is from wind loads (Sahlin, 1989). The practice of using the stadium for rock music concerts is a recent phenomenon and nothing related to this form of use is to be found in building codes and other regulations.

Before 1985 several rock music concerts were held in the stadium with audiences numbering several thousand. Vibrations were noticed even then (unpubl.) but as they were not too serious no action was taken.

The prohibition is a blow to the Gothenburg community, as takings for rock concerts can amount to $ 20 million per concert. Gothenburg is the second biggest city in Sweden and is situated close to the capitals of Norway, Denmark and Sweden. It attracts both megastars in rock music and huge audiences. As the musicians are often engaged years in advance it might take some time before the stadium is once again able to host a large concert, even if the problem is remedied today. It is clear that Nya Ullevi's plight is not unique. Wembley Stadium in London, capacity 100.000, a 50.000 seat stadium in Rotterdam and Slane Stadium in Dublin have all been faced with the problem of high vibrational level caused by rock concerts.

An attempt to reduce vibrations was made in the winter of 1986-87. Lime columns were installed over the entire area of the pitch in a quadratic pattern at alternate depths of 15 m and 8m. They were not connected and their centre to centre distance was twice their diameter. Installation decreased vibration levels by 15-20 % but this is not enough and the problem still awaits an economically feasible solution.

The hypothesis of this paper is that the audience on the pitch excited the soil layer so that its movements conducted through the piles contributed to the excitation of the stadium building.

The purpose of this paper is to present the damage together with observations of the vibrations with an explanation of their magnitude.

THE NYA ULLEVI STADIUM

Nya Ullevi Stadium is founded on hammered pre-cast concrete piles, see fig. 2. They are both cohesional and point bearing. The point bearing piles are driven into firmer ground which most often is a thin moraine layer. The thickness of the moraine layer is irregular from 0 -5 meters with a mean thickness of about 2 m.

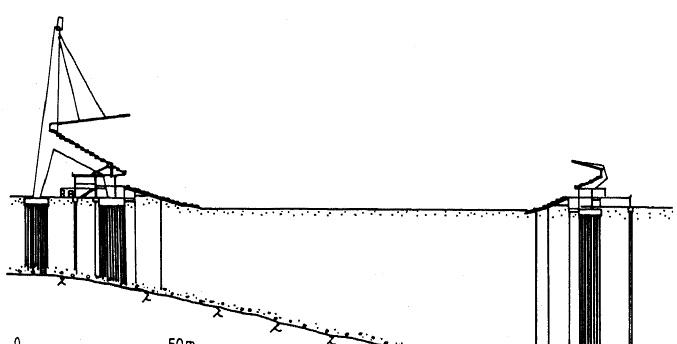


Fig. 2. Cross Section of Nya Ullevi Stadium. Profile A-A from fig. 1.

The roof forms an oval structure with an inten circumference of about 500 m. It is very flexible with lowest eigenfrequency below 1 Hz. Above one of the lc sides it is wide and projects onto two tall pylons, ea carrying 16 wires holding the roof in place. On the other lc side steel cantilever beams protruding from a heavy concr structure comprise the roof and support the stands (Sahl 1989).

From recorded pile depths and test holes in the field depth the bedrock have been mapped, fig. 3. The boundary betwe clay and granite is inclined with many irregularities. T deposit thickness is about 15-25 m in the N-W part of arena and increases in a S-E direction with maximum dep of 60 m in a rock depression under the field about 20 m fr the south east shortline of the field. The depth then decrea rapidly. Under the south east part of the structure the deptl between 15 and 40 m. The stage was located in the N-W p of the pitch immediately behind the goal.

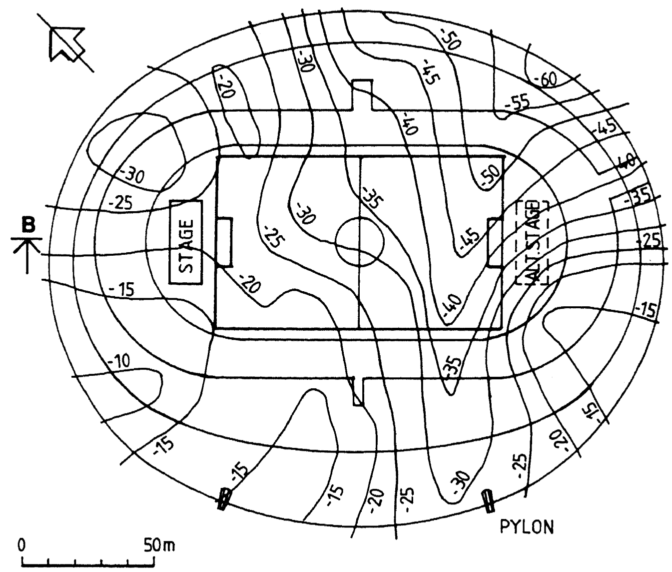


Fig. 3. Plan of Nya Ullevi Stadium showing clay depo thicknesses. The stage and the alternative location of stage are shown.

As the surface of the bedrock is very asymmetrica proposed solution was to relocate the stage at the other e of the field where the audience would be accomodated o the deep part of the clay layer, see fig. 3. The clay wo then be excited in a different way which it was hoped wo diminish vibrations. The paper present calculations for b of these modes of excitation.

THE GEOTECHNICAL PARAMETERS

A typical soil profile together with some basic geotechni properties is shown in fig. 4. The typical deposit mate consists of quite uniform high-plastic clay. The undrai shear strength τ_{fu} is about 20 kPa at 4 meters depth and increases slowly with depth to a value of almost 35 kPa at 20 meters depth. The sensitivity S_t is very high mainly between 10-20. The total unit weight of the material is nearly constant with depth and has a mean value close to 1550 kg/m^3. The natural water content w_n and the cone liquid limit w_F have about the same value, around 80 % except in the silty clay layer at depths between 7 and 9 m were they decrease to about 50 %. The plasticity index I_p is normally in the range 60-80 %. The material is most often normally consolidated with OCR close to unity.

The initial shear modulus G_0 for Swedish clay can be estimated from the relationship (Andreasson, 1979)

$$\frac{G_0}{\tau_{fu}} = 500 \qquad (1)$$

where the shear strength τ_{fu} is given in fig. 4. This gives G_0 = 10 MPa at 4 m depth and G_0 = 17.5 MPa at 20 m depth.

The damping properties of Gothenburg clay were studied by Andreasson (1979) in the resonant column apparatus. In the small strain range ($\gamma \leq 10^{-2}$ %) the damping ratio D can be assumed to be constant equal to D = 0.02.

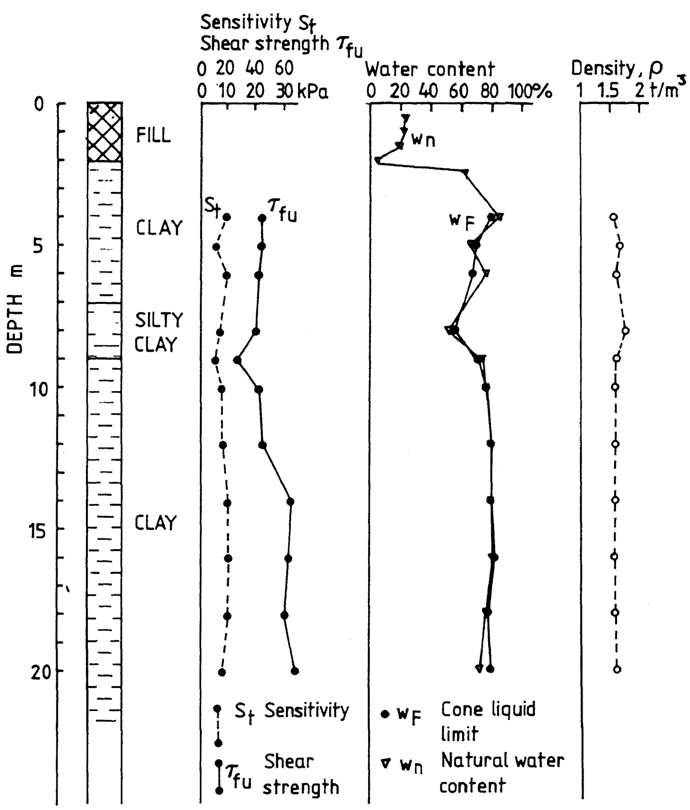


Fig. 4. Typical soil profile with some geotechnical parameters in the Nya Ullevi Stadium area.

OBSERVATIONS OF VIBRATION AND DAMAGE

During the concerts a number of those present observed considerable motions in the stadium and the ground. In particular stadium staff on duty at the time experienced significant movement inside the building although actual damage was only observed afterwards.

The following is a summary of the observations made during the concerts (unpubl.). One of the wires from the south pylon vibrated heavily (a in fig. 1). The maximum displacement amplitude was assessed at 5 to 30 cm by different observers. The movement was very irregular. The roof moved substantially up and down.

The upper parts of the stands (b in fig. 1) moved so violently that some of the audience left their places. The stands closest to the stage vibrated substantially. Beneath the stands in the north east part of the stadium where the organisers offices were located (c in fig. 1) some people left the rooms for fear of structural collapse.

Heavy ground vibrations were also noticed and were assessed by different people to have an amplitude of displacement between 2 to 20 cm. There is one direct observation of relative motion between the ground and the concrete foundation of the building (d in fig. 1). A crack was observed which opened and closed with a maximum opening of 15 - 20 mm. Vibrations were observed in buildings at Odinplatsen situated 400 meters north east of the stadium. Residents complained that the vibrations were sufficiently severe to shake ornaments and cause books to tumble from shelves.

Some of the interviewed persons claimed that the audience jumped with a beat only half of the beat of the music. This has been interpreted as a misunderstanding of the fact that the audience jumped off-beat.

Damage was limited to three items. One of the plates in the ceiling supporting an attachment for the wires was deformed (e in fig. 1). A window frame in the wall below the upper stands was broken (f in fig. 1). The window had to be repaired immediately. A waste pipe was believed to have been broken during the concerts (g in fig. 1).

NUMERICAL ANALYSIS

A two dimensional finite element analysis has been carried out to analyse the problem using the finite element package ABAQUS (Hibbitt et. al. 1989), fig. 5. Four node bilinear plain strain elements were used. The internal damping was assumed to be of hysteretic nature corresponding to a damping constant D = 0.02. Viscous dashpots were placed on the sides of the mesh to model the infinite domain.

Sahlin (1987) investigated load-time function of jumping people to Bruce Springsteen's rock music. Based on his results the dynamic load can be estimated from

$$\sigma = \sigma_0 \left[\sin \omega_1 t + 0.2\sin\left(2\omega_1 t - \frac{\pi}{4}\right)\right] \quad (2)$$

where $f_1 = \omega_1/2\pi$ is close to 2.4. The amplitude σ_0 can be approximated to be $\sigma_0 = 3.0$ kPa which corresponds to 4-5 persons/m^2 (Erlingsson and Bodare, 1993; Berglund and Erlingsson, 1992).

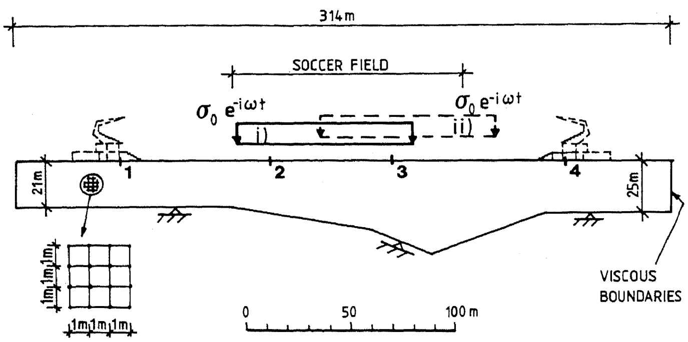


Fig. 5. The finite element mesh showing the two loading cases and the location of observation points 1, 2, 3 and 4. Profile B-B from fig. 3.

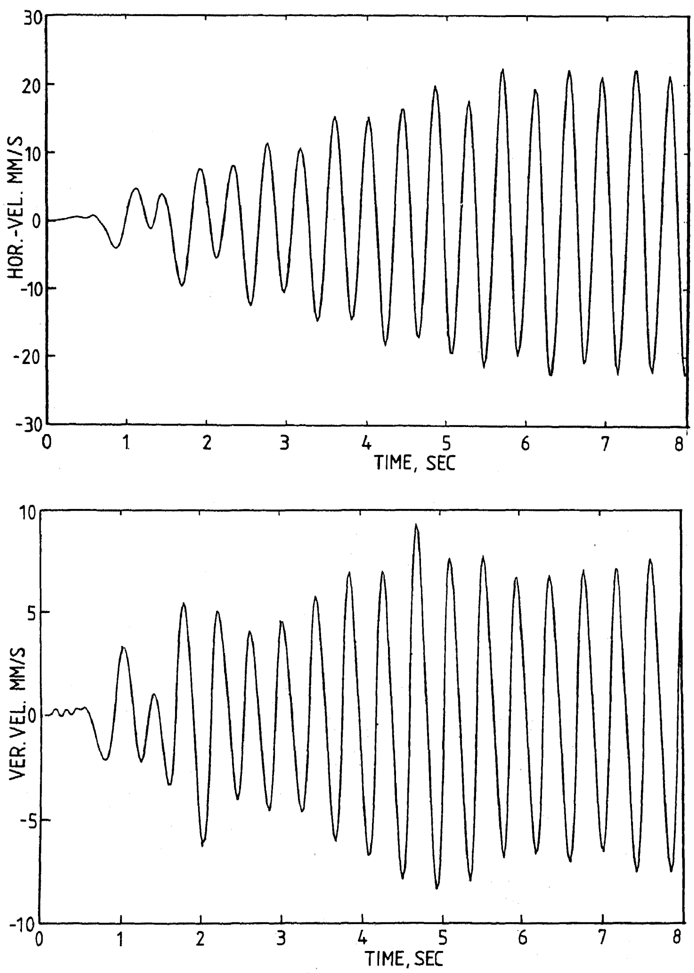


Fig. 6. Plot of velocity versus time for point 4, loading case i). a) horizontal direction, b) vertical direction.

The finite element mesh used in the analysis is shown in fig. 5 together with the two loading cases i) and ii). Location of observation points 1, 2, 3, and 4 are also shown. Points 1 and 4 are located on the surface under the building. Points 2 and 3 are located on the field.

The results are shown in fig. 6 and in table I and II. In fig. 6 the horizontal a) and the vertical b) velocities of point 4 (se fig. 5) are plotted as a function of time. It can be seen from fig. a) that the horizontal vibration amplitudes increase gradually until they stagnate at a value of 22 mm/s after about 6 seconds. It takes thus about 14 cycles to build up the maximum vibration amplitude.

TABLE I. Maximum velocity amplitude in the horizontal direction for points 1, 2, 3 and 4.

Case	Output point			
	1	2	3	4
i)	6	24	13	22
ii)	3	32	15	29

TABLE II. Maximum velocity amplitude in the vertical direction for points 1, 2, 3 and 4.

Case	Vertical velocity amplitudes [mm/s]			
	Output point			
	1	2	3	4
i)	10	12	19	8
ii)	6	20	4	8

The amplitude in the vertical direction builds up faster and achieves maximum value after about 10 cycles thereafter decreasing somewhat and stabilising at a value of 8 mm/s after about 6 seconds. The horizontal amplitude is here almost 3 times greater than the vertical one even though the dynamic load is only acting in the vertical direction.

The maximum amplitudes for the observation points in fig. 5 in both the horizontal and the vertical direction are given in tables I and II. Two cases are shown: i) the true case and ii) the case where the stage has been moved to the alternative location behind the other goal, see fig. 1. The vibrational amplitudes vary from 6 to 24 mm/s for case i) and from 3 to 32 mm/s for case ii). The horizontal amplitudes are somewhat greater than the vertical one except for point 1.

The relationship between the natural frequencies and the deposit thickness H for a uniform soil is (Roësset, 1977)

$$f_n = \frac{(2n-1)}{4}\frac{c}{H} \qquad n = 1, 2, 3 \ldots \quad (3)$$

where c is either shear- or compression- wave velocity respectively and the number n represent the number of modes. Using the mean shear wave velocity $\bar{c}_s$ in the analysis the resonance depth can be estimated, see table III.

TABLE III. Resonance depths of the soil layer.

Mode n	Mean shear velocity $\bar{c}_s$ [mm/s]	Resonance depth H_n [m]
1	70	7
2	80	25
3	90	46

The deposit thickness in points 2 and 4 are around 25 m, a value which corresponds very well with the natural depth for the second mode. This explains the high horizontal vibration level of values over 20 mm/s for both cases i) and ii) in table I.

Using similar reasoning as above for the compressional wave velocity a resonance depth of over 60 m is obtained. This is obviously not the case. The static deflections Δ due to the load can easily be estimated from

$$\Delta = \frac{\sigma_0}{3G_0} H \tag{4}$$

where σ is the applied stress and H is the deposit thickness. This gives Δ = 0.7 to 1.3 mm amplitude for deposit thicknesses H between 20 and 40 m or corresponding velocities amplitudes between 10 and 20 mm/s. This is in good agreement with the amplitude for points 2 and 3 in loading case i) in table II. The amplitude for point 3 of loading case ii) is on the other hand much smaller, only 4 mm/s even though it is under the external load. The vertical amplitudes under the stadium, points 1 and 4, are somewhat smaller as the waves become attenuated when spreading out from the source.

The German building code DIN 4150 part 3 states that vibrational levels over 20 mm/s for this range of frequencies can lead to a risk of damage. The analysis shows that this critical value was exceeded in the horizontal direction but the vertical amplitudes were somewhat smaller. This may explain the damage which occurred and the high vibrational levels experienced in and around the stadium.

CONCLUSIONS

It has been found that the high vibration levels noticed during the concerts can be explained by resonance of the soil deposit. By accident the beat of the music coincided with the first overtone of the clay layer. High vibration levels are obtained by the numerical simulation, which also shows that the horizontal displacement amplitudes may be greater than the vertical amplitudes for many points in the soil. It is also shown that a movement of the stage to the other end of the field does not decrease the vibration levels enough to offer a practical solution.

ACKNOWLEDGEMENTS

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