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Determination of Expected Damage of Building due to Vibration Loading. A Comparison of the Estimating Methods

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SUMMARY The paper deals with the theories used in Hungary to determine the expected damage of buildings due to vibration loading. There is no state standard in this field in Hungary therefore Hungarian practice is based on the scale numbers of damage used in the literature and foreign standards. This situation demanded the comparison of the different methods. The analysis of the measured vibration of a building using the different theories led to various results. The same measured vibration parameters have been estimated using the methods as follows: Zeller, Crandell, Pal, Soliman, Ciesielski, DIN, KDT-RICHTLINIE, Hungarian General Explosion Standard, Gustafsson-Hall and O'Neil. The evaluation covers building damage not to be expected as well as definite structure damage to be expected depending upon the method of estimation. The outcome of the study strongly emphasized that the evaluation of the building damage to be expected due to vibration loading is very subjective and depends not only on the method chosen but mainly on the investigator's experience.

Symbols used throughout the paper are as given in SI units.

K = Zeller coefficient
a = Vibration acceleration
f = Vibration frequency
A = Displacement amplitude
ω = Arc velocity
V = Vibration velocity
S = Pal number
E = Crandell number

1 INTRODUCTION

In the practice of the building industry we often have to decide whether vibrational loading increased for one reason or another /set of piles, bulkhead, changes in traffic, explosion, etc./ could cause damage in engineering structures, public supplies, buildings surrounding the vibration source. The vibration effects caused by industry and the building industry must also be taken into account in the planning and construction of new projects.

The aims of vibrational tests are threefold. Firstly, knowing the vibrational characteristics, the overloads caused by dynamic load have to be determined in the separate building units, secondly the building has to be studied in its entirety in order to determine on the basis of the measured parameters the occurrence probability of the general deterioration of strength or aesthetical loss. It needs to be studied, thirdly, whether vibrations could cause an undesirable settlement in the subsoil, as building damage can occur in that case when vibrations do no damage to the building but weaken the subsoil and the subsidence that occurs cause the static type deterioration of the superstructure.

Because of the limited length of the following paper I deal only with the review and comparative study of the theories on determination of general deterioration of structural integrity to be expected as an effect of vibrational loading.

2 SCALE NUMBERS INDICATING THE PROBABILITY OF DAMAGE

The scale numbers of damage known from the literature are practical limits of statistical characteristics, showing the probability of the deterioration of structural integrity and, generally refer to buildings in good condition. It is important to know, because vibrations doing no damage to a building in good condition can cause further deterioration to structural units already damaged. The ten most frequently used scale numbers of damage used in Hungary will be discussed below.

2.1 Zeller Coefficient

The more exact index can be obtained from the vibration acceleration:

$$K = \frac{a^2}{f} = \frac{/A\omega^2/^2}{f} = 16\pi^4 f^3 A^2 \quad /mm^2/s^3 \qquad /1/$$

The range of the Zeller scale concerning the deterioration of structural integrity of the building:

K mm^2/s^3	Danger group	Effect	Building damage
K<5000	I-III	light	building damage is not probable
5000<K<25000	IV	can be measured	no structural building damage can be expected
K>25000	V-XII	moderate-	structural building damage

K mm^2/s^3	Danger group	Effect	Building damage
		-great territorial catastrophe	can occur

2.2 Crandell Number

It is based on the swing by mass unit:

$$E = 16\pi^4 A^2 f^2 \quad /mm^2/s^2/ \qquad /2/$$

$E < 2000\ mm^2/s^2$	building damage is not probable
$2000\ mm^2/s^2 < E < 4000\ mm^2/s^2$	minor damage in the buildings can be expected
$E > 4000\ mm^2/s^2$	greater damage in the buildings can be expected

2.3 Pal Scale

$$S = 10\ \lg\ /\frac{V}{V_o}/^2 \qquad /-/$$

$$V = A\omega = A2\pi f \quad /mm/s/ \qquad /3/$$

$V_o = 0.316$ mm/s experimental limit of vibration detection

For the evaluation of Pal values see the table below:

0 -30 Pal	building damage cannot be expected
30-40 Pal	minor damage in the buildings is possible
40-50 Pal	greater damage in the buildings can be expected
50-60 Pal	definite building damage

2.4 Soliman's Degree of Safety

Soliman formed a new dimensionless index comparing the different indices used in the literature taking the mean from them. The nomogram practically demonstrating the indeces suggested by him is shown in Fig 1.

2.5 Ciesielski diagram

On the basis of his experiments Ciesielski set up a graph concerning the effect of vibrations on the building.

Fig 2 and Fig 3 show the Ciesielski diagrams referring to low /h/b<1/ and high buildings /h/b>1/ where h=height, b=width. The ranges marked with roman numbers are as follows:

I. The vibration has no deleterious effect
II. The vibration can be detected but the safety of the building is not in danger
III. Local cracks, diminished load bearing capacity
IV. Greater danger of structure deterioration, local collapses can be expected
V. There is some danger of total collapse

The limits marked by points and dashes refer to the buildings of better quality, standing on better soil, the limits with a continuous line refer to the buildings standing on poorer soil or having a worse condition.

2.6 Specifications of DIN 4150/1975

According to the DIN specifications the resultant of the vibration velocity:

$$V_{Rmax} = \sqrt{/V_x{}^2 + V_y{}^2 + V_z{}^2/max} \qquad /4/$$

has to be compared with the limit velocity values given in the specification. The simultaneous measurement of the three velocity components figuring in the formula which are perpendicular to each other is possible only with a three-channel device, so for safety the summary of non-simultaneous maxima determined by a one-channel device can also be applied according to the formula:

$$V_R = \sqrt{V_x{}^2 max + V_y{}^2 max + V_z{}^2 max} \quad /m/s/ \qquad /5/$$

The velocity limits are as follows:

$1{,}57 \cdot 10^{-1}$ mm/s	Detection threshold
$1{,}57 \cdot 10^{-1} < V_R < 2{,}50$ m/s	Damage excluded
$2{,}50$ mm/s $< V_R < 6{,}0$ mm/s	Damage cannot be expected
$6{,}0\ V_R\ 1{,}0 \cdot 1{,}0 \cdot 10^{-1}$ mm/s	Damage is not probable but control investigation of tension is recommended
$1{,}0 \cdot 10^1$ mm/s $< V_R$	Investigation of tension is essential, damage is possible

2.7 Specifications of KDT-Richtlinie 046/72

The specification studies the effects of explosion vibration concerning the types of buildings. Fig 4 shows the values of vibration velocities allowed as a function of frequency. In the figure the ranges marked with roman numbers are as follows:

I. monument buildings
II. bricksets
III. wall-structure buildings /slat, block, etc./
IV. skeleton buildings made of steel or reinforced concrete, perhaps of wood

2.8 Specifications of ÁRBSZ-1973.

The General Explosion Security Specification /ÁRBSZ/ lists the allowed maximum vibration velocities depending on the type of the building in the following table:

Type of the establishment	Maximum vibration velocity allowed /v/ mm/s
Establishment requiring a special protection /i.e. establishment of national defence and telecommunication, airport, dam, bridge with a span more than 20m/	according to the experts's opinion

Type of the establishment	Maximum vibration velocity allowed /v/ mm/s
Statically unbalanced, damaged building, monument, pipeline under pressure and its establishments	2
Building of not-full value statically, oil and gas well	5
Statically perfect buidling, tower, factory chimney, electric and water works, open air electrical equipment	10
Steel or reinforced concrete skeleton building, tunnel, underground area	20
Highway, railway, suspension railway, electrical transmission line, telephone line	50

2.9 Swedish proposal by Gustafsson-Hall

The allowed vibration velocity limits are given as a function of the velocity of propagation of an acoustic wave propagating in the soil, these are demonstrated by the table below:

TABLE

	Rock of the Subsoil		
	Sand, pebble wet caly	moraine, slate, soft limestone	hard limestone, quartz, granite, gneiss, diabase
Velocity of propagation of the acoustic waves /mm/s/ in the rock	$1000 \cdot 10^3$- $15000 \cdot 10^3$	$2000 \cdot 10^3$- $3000 \cdot 10^3$	$4500 \cdot 10^3$- $6000 \cdot 10^3$
	Allowed Vibration Velocity mm/s		
1. There is no damage	18	35	70
2. Fine cracks, falling of plasters /limit/	30	55	100
3. Formation of strong cracks	40	80	150
4. Extended damage	60	115	225

2.10 Vibrational plot of pile-driving by O'Neill

The diagram shown in Fig 5 represents the ranges corresponding to various building damage as a function of amplitude and frequency according to O'Neill.

3 A COMPARATIVE STUDY OF DIFFERENT SCALE VALUES OF DAMAGE

One part of the theories, as it has been shown above, supplies velocity limits, the other part gives effects based on the amplitude and frequency. Without aiming at completeness, in order to compare the ten damage indices chosen it was necessary to convert them to the same dimension. Therefore the limits in the specifications were converted to vibration velocity limit /dimension: mm/s/.

6-25 Hz frequency spectrum was considered as a basis of the calculation because the many years' experience in vibration measurements shows that the vibrations of buildings spreading through the soil are mainly within this frequency range.

The vibration velocity limits were calculated to two extremes of the frequency spectrum /6 Hz and 25 Hz/ separately in the case of those indices that gave no velocity limits. At first fixing the frequency, the value of the amplitude was back calculated so that the limit of the theory used /i.e. Zeller/ remained constant /i.e. $Ke=5000$ mm^2/s^3/. Subsequently the vibration velocity limit was calculated from the corresponding amplitude and frequency values.

Taking as an example the Zeller's shock coefficient to a $K=5000$ mm^2/s^3 damage limit, at 6 Hz frequency this corresponds to a $v_1=4,60$ mm/s vibration velocity limit, at 25 Hz frequency this is $v_1=2,25$ mm/s.

The different theories express the damage phenomena to be expected in a different way. Almost each contains a limit, where building damage cannot be expected, moreover a threshold value above which structural damage of the building can be expected. According to this a v_1 and v_2 limit was taken into consideration from these theories in such a way that if effective vibration velocity

$v < v_1$	building damage cannot be expected
if $v_1 < v < v_2$	less, non-structural building damage can occur
if $v_2 < v$	structural building damage can be expected

The vibration velocity limits determined in the way described are compiled in the table below:

TABLE

Index	Frequency	v_1 /mm/s/	v_2 /mm/s/	v_2/v_1
Zeller	6 25	4,60 2,25	10,30 5,03	2,2 2,1
Crandell	6 25	7,13 7,12	10,10 10,10	1,4 1,4
Pal	-	10,00	31,60	3,2
Soliman	-	13,70	-	-
Ciesielski	6 25	4,34 1,18	20,70 5,81	4,8 4,9
DIN	-	6,00	10,00	1,7
KDT-Richtlinie	-	5,00	10,00	2,0
ÁRBSZ	-	10,00	-	-
Gustafsson-Hall	-	18,00	40,00	2,2
O'Neill	6 25	2,07 1,02	26,00 11,90	12,6 11,6
$\frac{\max}{\min}$	-	18,0	8,0	9,0

The table points out the following:

- The ratio of the maximum and minimum of the given v_1 threshold values is 18,0 and that of the v_2 values is 8,0. Thus, according to one theory a certain v_1 value can be expected to cause building damage whilst another theory forecasts a 18,0 times greater velocity as being necessary.

- The ratio of the two limits /$\frac{v_2}{v_1}$/ of the given theories shows how many times bigger than the damage threshold the velocity must be to cause structural building damage. In such a sense 1,4 and 12,6 are the two extremes. Thus according to one theory only 1,4 times the lower limit can already cause structural building damage but according to the other 12,6 times the lower limit has the same effect. The ratio of the largest and smallest range is 9,0.

- For example if the vibration velocity measured on the building is 5,5 mm/s /vibration of 25 Hz frequency/ let's study the probability of the damage using the different theories.

According to Zeller	structural building damage can be expected
According to Ciesielski and KDT-Richtlinie	smaller, non-structural building damage can be expected
According to O'Neill and the other theories studied	building damage cannot be expected

Thus, on the basis of the vibrational velocity value given in the example the investigator could establish any one of the damaging probabilities depending on the theory used for the evaluation of the vibration test results.

It can be seen from the above that for lack of national regulation the evaluation of the vibration test results concerning the general damage is highly subjective. This calls attention to the need for the earliest possible elaboration of national regulation.

It would be expedient to elaborate the dynamic standards in accordance with the static ones. From the vibrational parameters the vibration acceleration should be taken as a basis because according to the experiences the building structures are most sensitive to the change in the acceleration.

SOLIMAN Degree of safety

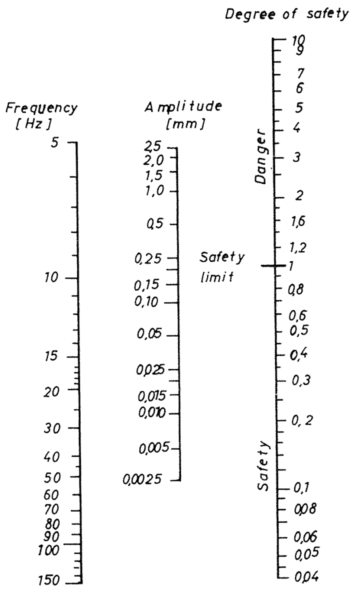


Figure 1.

„CIESIELSKI" DIAGRAM
for low buildings ($\frac{h}{b} < 1$)

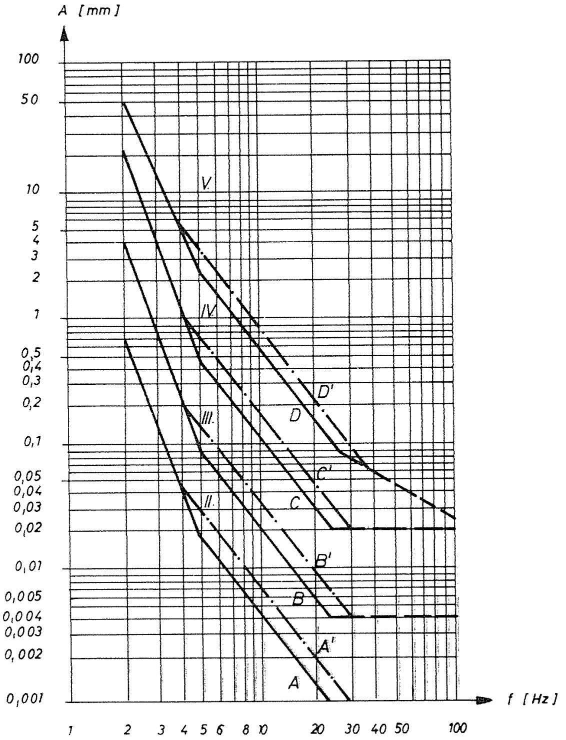


Figure 2.

„CIESIELSKI" DIAGRAM
for high buildings $(1 > \frac{h}{b} \leq 2)$

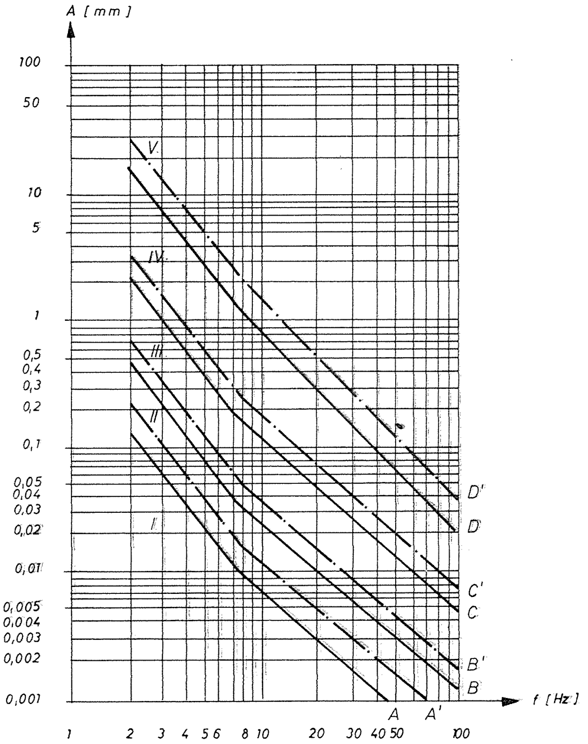


Figure 3.

KDT 046/72 Specifications

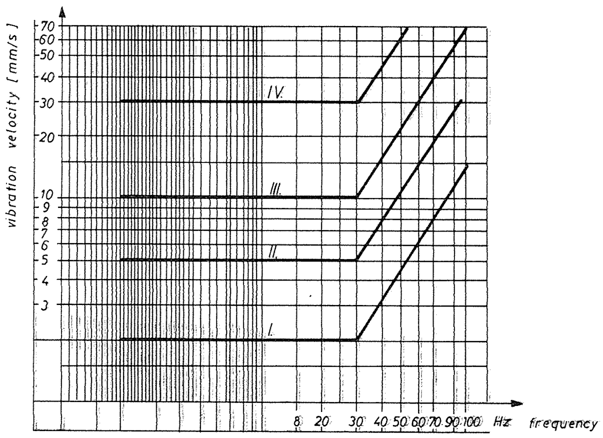
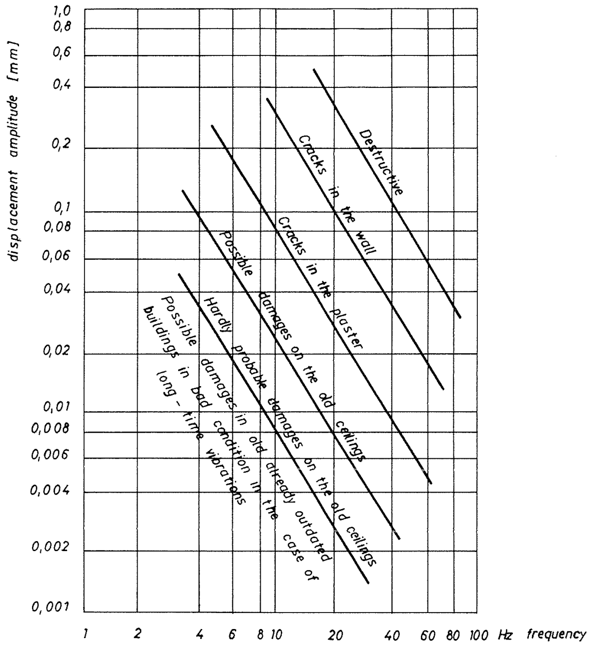


Figure 4.



Vibrational plot of pile - driving by O'Neill

Figure 5