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BUILDING BASE ISOLATION RECENT PROGRESS, FEEDBACK AND PRACTICAL HINTS

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1 SUMMARY

An overview of the historical backgrounds of building base isolation (=BBI), the state-of-the-art and practical design recommendations are presented. We introduce a new simple concept that allows an easy evaluation of the transmission loss of a base–isolated building based on the amount of mass that co-operates in the dynamic response. This concept needs to be handled with care and attention, because it does not allow to make appear structural resonances that might affect the efficiency locally.

2 INTRODUCTION:

BBI techniques are in use since quite a number of decades. They have been applied to buildings to protect them mainly for 2 different reasons (1) casualties and damages caused by subsidence and seismic activity and (2) acoustic and vibration discomfort and malfunctioning caused by low amplitude ground-borne vibrations.

The first field is beyond the scope of this conference and the reader is referred to the vast technical literature ; for first impressions and analytical background see e.g. [1], [2], [3], [4] and [5].

The second field has started to make its appearance in building technology in the early 1960's and has since then evolved to become now a major field of investigation backed by years of experience and measured feed-back. The last years however there has been a consistent push towards technical and economical improvement.

The main problem in this field is quite simple to circumscribe.

- Ground-borne vibrations caused by rail-traffic (the number one source !) are mainly centred in the 40 to 100 Hz. region, with amplitudes ranging from 60 to 80 dBV (ref.5^{E}-8 m/sec) at the building foundation level (the excitation spectrum).
- When one has defined an acceptable comfort level in the building (e.g. based on the "American Public Transit Association – Guidelines for design of rapid transit facilities – 1981"), e.g. Lp,max = 35 dBA, one can make the calculation to come to the mobility to be inserted into the building in order to reduce the amount of vibrations. In most cases, the requirements will be anywhere between 5 and 20 dBV in the spectral area of interest (40 to 100 Hz.)
  But...in practice? Which questions an acoustic consultant is confronted with when dealing with a BBI project ?
- **The « model » questions** : What model do I use and how detailed do I make that model ? Where do I put the vibration isolation cut ? What input spectrum do I use ? Once the model is OK......
- **The « system » questions** : What is the required degree of isolation in accordance with an acceptable comfort level ? Which vibration isolation system do I choose and which information do I require from vibration isolation system suppliers to make my study as accurate as possible? Once the model is OK , the parameters are OK and the materials have been chosen....
- **The « execution » questions** : How accurate can a BBI system be actually executed ? What specific requirements do I introduce in the specs so to make the contractor fully aware of the vibration cut over the full building construction period ? How do I control the efficiency of vibration isolators ? Once the model is OK, the parameters are OK, the supplied materials are OK and the execution is OK,....
- **The « control » questions** : how can I measure « a posteriori » the efficiency of the built-in system ?

3 HISTORICAL BACKGROUNDS

The reply to the 4 questions is better explained by retracing in brief lines the history of BBI against ground-borne vibrations. The field has indeed known a very interesting history that can be divided into 3 different periods:

- In the early years (1950-1970) – « the pioneer period », BBI techniques consisted in cutting the building on a certain level and provide on the supporting surfaces a number of rubber bearings (natural rubber and chloroprene) to carry the building. These bearings were designed based on technology and engineering practice coming from the bridge-bearing field, where the main design concern was the horizontal displacement capability. The rubber bearings were in most cases too stiff to provide high degrees of isolation. This was mainly due to the fact that the engineers were afraid to introduce too much flexibility into the building (the early days) and later on when some degree of flexibility became gradually more accepted, the design process to come to reliable dynamic properties of the bearing system and to understand the behaviour of building on elastomers was not correct. The errors were mainly based on 2 mis-understandings :
  a) the vibration isolation efficiency of rubber bearings was measured in terms of a theoretical resonance frequency extrapolated from the vertical deflection of the bearing
  b) the building was modelled as a SDOF (a mass on a spring-damper).
  Some of the base-isolated buildings from this pioneer period have performed remarkably well (the small ones on stiff foundations), but the results of a vast majority were not worth speaking of. This is also probably the reason why until the 80's, practically no measured feedback could be found in the technical literature.
- As a result of these first experiences, there has been gradually a push towards extreme security, with application of very flexible spring-type solutions. This period goes from the 70's until the early 90's and can be called « the umbrella period », mainly due to the fact that the solutions based on helical springs (with resonance frequencies of the springs between 3 and 4 Hz.) were rarely non-successful but in a lot of cases they were over-designed. Resilient bearing projects were rarer in this period. Most of the buildings requiring isolation were indeed installed on spring-boxes. It was the economic recession during the 80's that created the need to study more adapted solutions. With the venue of economic computer time, more precise models and dynamic measurement techniques, the acoustic engineers were able to fine-tune the solutions and concluded that in some cases spring-type solutions could be replaced by more economic resilient systems.
- From the early 90's until present days we are in « the adult period » , where BBI profession has reached a high level of experience and market respect (although not fully mature). High sensitive and acoustically critical areas requiring high degrees of isolation (mostly > 15 to 20 dBV) are installed on spring-box type of solutions, where-as areas with lower isolation requirements (< 15 dBV) are now installed on high performance resilient materials. The author is expecting a 4th period which we probably will call « the mature period », because the 4 questions will have easy and straightforward replies, quickly to compute by using a model readily available on PC with reliable data concerning dynamic behaviour of the resilient systems.

4 THE 4 QUESTIONS ANALYSED

- **The « model » questions** : presently there are quite a number of models (see e.g. [6], [7], [8], [9], [10], [11], [12], [13] and [14]) and calculation techniques available ranging from very simple 3 or 4DOF models *(taking into account the different mobilities i.e. the infra-structure, the vibration isolation level, the part of the super-structure immediately above the vibration cut (i.e. the part that co-operates in the direct dynamic response,...in practical terms this is the first floor level above the vibration cut level) and the part of the super-structure that is less directly affected by the dynamic response (i.e. in practical terms the remaining floors*)) to complex finite elements models and SEA techniques. It is our understanding that simple models like the 3DOF model give in a lot of cases already sufficient feedback in order to make a choice of the correct vibration isolation system (low frequent at 3 to 4 Hz., mid frequent at 8 to 10 Hz. or high frequent at 13 to 15 Hz.) . The response to where to cut the building is a compromise between seeking enough inertial mass, stability of the building, aesthetics and of course financial cost. In present state-of-the-art most of the vibration cut levels are situated or immediately below ground floor level (pay attention to bridging via the soil ! !) or immediately below the first floor (the vibration cut is visible in the façade). As to the input spectrum, to be chosen, there are 2 options, or the rail-traffic already exists, meaning that the excitation can be pretty accurately measured, or the track is not yet there and one has to start from assumptions with similar trains and experimental models (see e.g. [8], [9], [10] and [11]) . A very simple concept that can be introduced in order to come to some sort of quick evaluation of the amount of transmission loss to be expected at a certain frequency (e.g. 63 Hz.) is to introduce a hypothetical resonance frequency $f^* = \sqrt{1/\alpha} * f_{SDOF}$ (with α= part of the total building mass co-operating in the dynamic motion or in simple cases 1/α = n = number of floors above the vibration cut and f_{SDOF} = resonance frequency of a SDOF installed on the projected isolator system) calculated by taking into account only a part of the total suspended mass; this f^* is then used in the normal SDOF transmissibility graphs ($\Delta L_{v,SDOF}$ = transmission loss calculated from SDOF system with total dynamic stiffness K_{tot} and total building mass M_{tot} calculated on basis of the acoustic design load ADL = G+Q/3). The total mass of the building is M_{tot} and consists of "n" times a mass M (mass concentrated per floor).In this concept we take into account that only the mass directly above the vibration isolation cut co-operates in the motion ($M^* = M_{tot}/n$).The following formulas (a, b, c and d) are self-explanatory.

$$f_{SDOF} = \frac{1}{2\pi}\sqrt{\frac{K_{tot}}{M_{tot}}} \quad \text{...........}(a)$$

$$\Delta L_{v,SDOF} \cong 40\log\frac{f}{f_{SDOF}} \quad \text{...........}(b)$$

$$f^* = \frac{1}{2\pi}\sqrt{\frac{K_{tot}}{M^*}} = \frac{1}{2\pi}\sqrt{\frac{K_{tot}}{\frac{M_{tot}}{n}}} = \sqrt{n} f_{SDOF} \quad \text{...........}(c)$$

$$\Delta L_v^* \cong 40\log\frac{f}{f^*} = 40\log\frac{f}{\sqrt{n} f_{SDOF}} = 40\log\frac{f}{f_{SDOF}} - 20\log(n) = \Delta L_{v,SDOF} - 20\log(n) \text{..........}(d)$$

This manipulation allows to account for the fact that only part of the total building mass in dynamically in motion and more in general ***__a correction factor ΔL ≈ 20*log(α)__*** (with α = the fraction of the total building mass M_{tot} co-operating in the motion, in other words $M^* = \alpha M_{tot}$). In case of buildings with n levels, α = 1/n and for most of the cases [n] varies between 4 and 10, with a mean value around 6,...meaning that practical correction factors vary between 12 and 20 dBV. This correction factor has to be deducted from the transmission loss $\Delta L_{v,SDOF}$ (see formula (d)). In par.6, we will study some field experiences and see that the values coincide with own field experience.
The general correction factor formula is thus (with α = fraction of the total building mass co-operating in the motion):

$$\Delta L_v^* \cong \Delta L_{v,SDOF} + 20\log\alpha \quad \text{...........}(e)$$

- **__The « system » questions__** : starting from the input spectrum and the model response in whatever accuracy, the acoustic consultant can choose the vibration isolation system and give indications to the structural design team of the necessary stiffness modifications or mass concentrations (see par.5) to be reached in the project. Present state-of-the-art allows 3 types of interventions (with or without replace-ability options), i.e. low frequent systems at 3 to 4 Hz. (springs) mid-frequent systems at 8 to 10 Hz. (high resilient elastomers) and high-frequent systems at 13 to 15 Hz. (elastomers). The system supplier should be able to give the necessary technical and engineering assistance and follow-up in order to make the project a success. As to the information expected from the system supplier, the major ones are (1) the information on dynamic behaviour in laboratory conditions (see e.g. [16] and [17]) or in controlled site conditions (as the concept proposed by Alain Fournol in [15]) and (2) the bearing distribution and installation drawing. With respect to normalisation and design guidelines, the state-of-the-art is presently fairly poor. The only document that gives presently a more or less consistent approach is BS-6177 - see [18].
- **__The « execution » questions__** : the success of building vibration isolation is like the strength of a chain,...the weakest link. The smallest "bridge" can indeed jeopardise the full concept. Installation and execution of a perfect vibration cut requires therefor from the building contractor

a constant vigilance to bridging the vibration cut (e.g. stairways, elevator cages, façade treatment, cladding, HVAC etc...). It is advised that the building team has at least one responsible for the control of the whole project ; this can be the acoustic consultant, the system supplier or more practical someone of the building contractor.

- **The « control » questions** : the question on "control measurements" is still a major issue not yet completely solved and therefor not yet standardised. The profession agrees on one thing,...what BBI is looking for is "insertion loss" in terms of interior back ground noise level, i.e. the difference between the background noise (i.e. interior building response) with and without isolation,...the only problem is that "insertion loss" cannot be physically measured. It is indeed hardly imaginable to erect the structure first without isolation and then to introduce the isolation in order to check the difference. What can be measured is the so-called transmission loss, i.e. the difference between the response of the building before and after the vibration cut. State-of-the-art has different ways and interventions to control a BBI project:
  - ⇒ Close transmission loss measurement concepts adopted in France (see [15]). In this case the vibration pick-ups are installed immediately below and above the vibration cut. Measurements are done on 1 point or at multiple points. Easy and quick execution but difficult for correct interpretation (measurements very sensitive to "bridges"). Cases are indeed known of buildings with low back ground noise level while trains are passing (e.g. 35 dBA) vs. not isolated buildings in the immediate vicinity under the same excitation (45-50 dBA), but with a very low close transmission loss directly over the vibration cut.
  - ⇒ Floor to floor transmission loss measurement technique with multiple pick-up points (see e.g. [6]). Complex and time-consuming but easier to interpret and closer to structure borne noise concept.

5 DESIGN RECOMMENDATIONS TAKEN FROM 30 YEARS EXPERIENCE

STANDARD SOLUTIONS	1. pre-compressed systems: steel springs (f< 5Hz) or resilient bearings (f >6-7Hz) 2. simple steel springs (f < 5 Hz) or resilient bearings (f > 6-7 Hz)
STIFFNESS SUPRA- AND INFRASTRUCTURE	1. very stiff compared to building not installed on isolators 2. concentrate a maximum of mass very close to the vibration cut level 3. use large bearing surfaces (e.g. designed to e.g.1.50 to 2.00 MPa) for 2 reasons: • to invite structural engineer to stiffen the structure automatically • resilient materials show better dynamic behaviour (creep and K_{dyn}/K_{stat} ratio !) 4. make sure floating structure is designed to take a differential deflection > 1/3 of the deflection under ADL (= acoustic design load = G + 1/3Q) 5. lateral /overturning stability ? (shear stops, isolated tension bolts and lateral buffers) 6. support surfaces : flat and without abrupt changes – recommended hor. Tolerance 1/1000
ACCESSIBILITY, REPLACEABILITY, MAINTENANCE AND VISUAL INSPECTION	1. all bearing systems to be accessible 2. min. height of workspace for accessibility H > 1.80 m. 3. in case no pre-compressed boxes are used, make sure to have enough extra space for flat jacks (on bearing surfaces or by designing the possibility to introduce consoles)
FAIL SAFE & FIRE RESISTANCE	1. allow extra space on the bearing surfaces for fail safe seats 2. make enough space available to allow fire cladding installation

6 EXAMPLE OF TYPICAL BUILDINGS

6.1 Cinema – Eurodisneypark in Marne La Vallée near Paris

In 1995, a major movie-theatre company in France decided to build a new cinema complex very near to the high-speed train line (< 7 m. for the closest point) in the Eurodisney area –

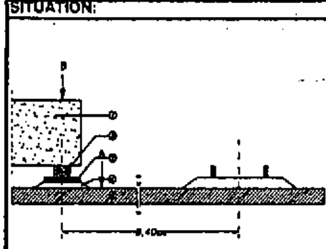
Marne La Vallée in France. It was decided to put the building on isolators immediately under the ground floor. The building structural concept was 2 storeys with relatively high ceilings (for movie-theatre) with a structural RC bearings walls and columns and cast in situ RC floors on large span longitudinal beams. The specifications asked for vibration isolators showing a resonance frequency around 8 to 10 Hz. under the project loads. The building construction team choose a CDM-ISO-STRUCTURE-SIMPLE system using CDM-81045 high resilience microcellular bearings loaded at approx. 2.5 MPa under the ADL (acoustic design load = G+1/3Q). It was decided to follow up very strictly the full installation process and to test the chosen bearings under different conditions using « transmission loss » techniques (i.e. compare the signal below and above the vibration cut under the same input spectrum):

a) In laboratory conditions further to ISO-10846 (see [16]) and [17]). The results obtained following ISO-10486 in a certified university lab and the CTS in the manufacturer's lab coincided (a $f_{res} \approx 8$ Hz. + very low dynamic stiffening). This information is available to the interested reader at simple request.
b) In controlled site conditions under a 12 T inertial block (SDOF) in the immediate vicinity of a railway following the procedures proposed by ref.[15]. Tested bearings 100x100x45 mm.
c) Prior to construction on site under a single heavy mass (also SDOF) with the correct input spectrum (i.e. the passing high-speed trains) by the acoustic consultant. Tested bearings 75x75x45 mm. (see [19])
d) After the construction was finalised in the theatre closest to the HSL.

In the following graphs, the comparable results of b (=case A), c (=case B) and d (=case C) are shown. The detailed analysis of these results is indeed very interesting.

CDM-ISO-STRUCTURE	TEST INFO SHEET CDM-81045	CDM-ISO-structure
CDM-product tested	CDM-81045 in 3 different locations all under same loading	
Test date & site	Aug. '95 and Mar. '96, Station of Rixensart, Belgium	
Executor	AVLS (test site) [20]+ Peutz & Associés (construction site) [19]	
Report references		
Test following		
Measuring	Transmission loss between ground velocity and inertial block velocity	
Description	A: test block 12 T CDM test site in Rixensart Belgium- B: test block Gaumont Disney Marne la Vallée C: after construction Gaumont Disney Movie Theatre	

SITUATION:



Legend 1. Concrete block of 12 T
2 Isolators
3 Steel repartition plate
4 Stabilised sand
5 Railway track

	T (dB)		
f in Hz	Case A	Case B	Case C
3.15	0	-2	0
4	0	-4	-12
5	-2	-7.2	-10
6	-4.5	-13.8	-6
8	-11	-19.1	-2
10	-17	-5	-2
12.5	-11.5	6.7	0
16	0	11.8	7
20	9	18.8	12
25	10	20.7	10
31.5	17	22.5	8
40	20	24.2	12
50	27.5	33.6	15
63	30	39.2	20
80	31	30.9	18
100	35	34	18
125	32	34	18

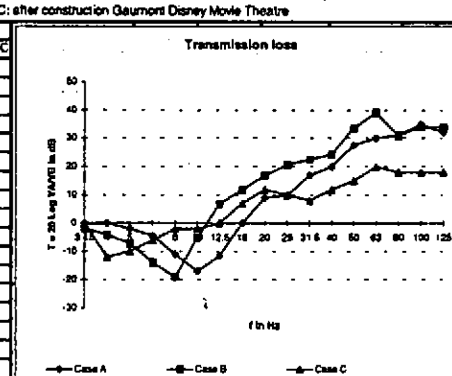


Figure 1 – Transmission loss EURODISNEY

Case A and B coincide pretty well (with a resonance frequency at approx. 8 to 10 Hz.), although the SDOF on the site resonated at a somewhat lower frequency ; this is mainly due to the fact that the isolation bearings used in case B (75x75x45 mm.) were smaller than the ones used in case A (100x100x45 mm), due to limitations of the inertial block on the site and to make them work under the same compression rate as in the project. The transmission loss in case C (i.e. the real MDOF) however is lower than the ones measured in SDOF conditions and confirms the fact that higher structural modes counter-act the normal expected efficiency. It can indeed be seen that the transmission loss reaches values of approx. 20 dBV versus a theoretical expected $\Delta_{Lv,SDOF}$= 32 dBV (at 63 Hz.) in case a SDOF-model is used with all mass concentrated above the vibration isolation level. This is mainly due to the existence of the modes of the longitudinal beams (around 25 – 30 Hz.) and the fact that not all the building mass is co-operating in the dynamic response. When these first series of measurements were taken, the BBI system was loaded with approx. 2 storeys (this was the first building phase,...in a latter stage an additional level was to be introduced (see par.6.2 for the influence). The cinema project had a specific design with very high ceilings so that we can take into account that only approx.25% of the total building mass was co-operating mass ($\alpha = 0.25$); this means that the $\Delta L = 20\log(0.25) = -12$ dBV If we apply this correction factor to the $\Delta L_{v,SDOF\,(63\,Hz)} = 32$ dBV, we are much closer to the reality, with approx. 20 dBV (at 63 Hz.) as result (to be compared with the measured 20 dBV. After construction, the back ground noise level generated by the passing HSL was measured to be 29 to 32 dBA, against 50 dBA calculated without isolation (see [19]).

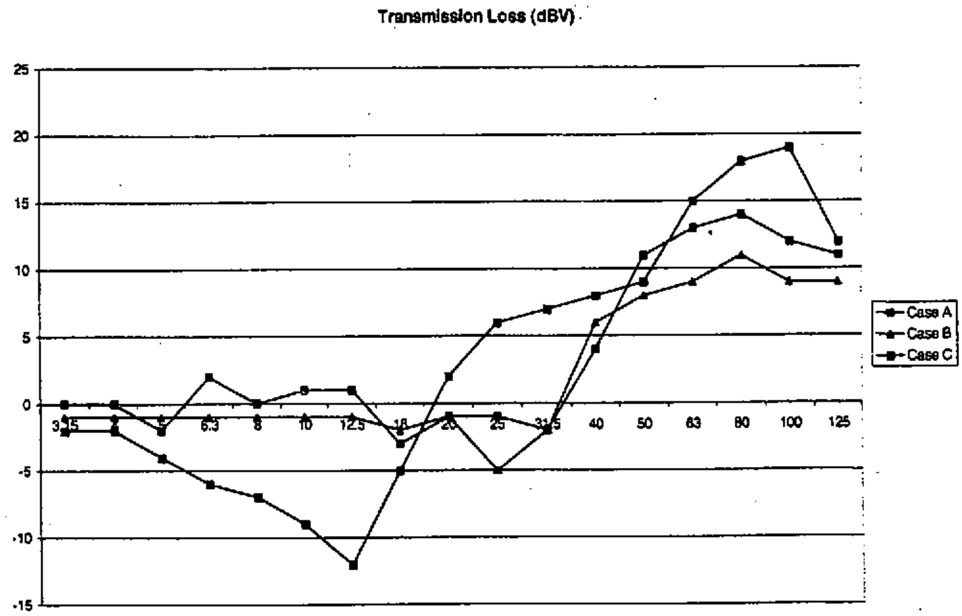
6.2 Vibration measurements on different buildings in and around Paris

In November 1999, we have launched an extensive measurement campaign on different buildings in and around Paris (see figure 2)

⇒ Case A : Cinema in Eurodisneypark (see also 6.1) with 1 extra storey. The total building mass fraction co-operating was now only 0.20 with $\Delta L = -14$ dBV. The real $\Delta L_{v,\,real} = 15$ dBV and coincides again pretty well with $\Delta L^{*} = 18$ dBV (= 32 – 14)

⇒ Case B :Hotel Orion in downtown Paris – Bd.de Grenelle with main excitation at 40-80 Hz. (63 Hz.) The BBI system was designed on f_{SDOF}= 10-12 Hz. (the goal was to reach -10 dBV @ 63 Hz.). The total building mass fraction co-operating was 0.16 (n = 6 levels above BBI system) with $\Delta L = -16$ dBV. The real $\Delta L_{v,\,real} = 10$ dBV and coincides again pretty well with $\Delta L^{*} = 13$ dBV (= 29 – 16).

⇒ Case C : Appartement Building in downtown Paris – Rue du Gabon with main excitation @ 63-80 Hz. The BBI system was designed on f_{SDOF}= 4 Hz. (the goal was to reach -20 dBV @ 63 Hz.). The total building mass fraction co-operating during the measurements (building was 90% loaded – 6 levels above BBI) was thus 0.90*0.16 =0.14 with $\Delta L = -17$ dBV. The real $\Delta L_{v,\,real} = 15$ dBV and lags seriously behind with respect $\Delta L^{*} = 27$dBV (= 44 – 17). I f we study more in dept the TL graph however we see that the actual low frequency resonance is noted @ 10 Hz. (probably because the building was not yet totally completed there was probably still some lateral form work and temporal bridging to be taken away); if we take this last frequency with expected $\Delta L^{*} = 15$dBV (= 32 – 17) we find better compliance.



7 CONCLUSIONS

We have introduced a simple concept to have a better evaluation of the real transmission loss when installing a BBI system in a building. The concept is based on the introduction of a correction factor $\Delta L = 20\log\alpha$, α = building mass fraction co-operating in the dynamic motion

directly above the BBI-system) to be applied to the theoretical transmission loss calculated by taking into account that the whole building is acting like an SDOF on the BBI-system.
In the field measurements we have found pretty good matching between the expected and measured values, with the measured values always lagging a few dBV (< 3 dBV) behind; this is most likely due to complex structural behaviour.This last conclusion proofs that the proposed concept needs to be handled with care and attention, because it does not allow to make appear structural resonances that might affect the efficiency locally.

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