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Beyond Natural Frequency - a technical journey of key factors and choices in the successful design and execution of building vibration isolation projects, to ensure the client gets what they want

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BEYOND NATURAL FREQUENCY – A TECHNICAL JOURNEY OF KEY FACTORS AND CHOICES IN THE SUCCESSFUL DESIGN AND EXECUTION OF BUILDING VIBRATION ISOLATION PROJECTS TO ENSURE THE CLIENT GETS WHAT THEY WANT

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hotel building in a location that is likely to suffer the effects of ground / structure-borne noise e.g. from rail, nightclubs or factories. Initially they are reliant on the recommendations of the acoustic consultant where it is accepted that there will be margins of error in any prediction. There is therefore a critical reliance on a well-co-ordinated design (often under time pressure) and well executed construction (almost always under time pressure) in order to ensure that the sketch in the acoustic consultant's specification, of a building with a simplified isolation line through it, is translated into the finished building that really is fit for purpose for its intended inhabitants and that is delivered on time and on budget. During that process there will be a number of key decisions that have to be made in relation to the building isolation system and those decisions can have huge implications on the pro-gramme and budget so it is important that they are effective. Drawing from a number of real world case studies, this paper provides insights into a number of technical aspects, key decisions and effective solutions developed for a variety of buildings including complex multi-level basement structures, tall buildings (using an example of a 30 storey tower) and over station developments.

Keywords: building vibration isolation, structure-borne noise

1. Introduction

Whilst we as an industry must seek to further improve and share knowledge and capabilities to predict the behaviours of ground/ structure-borne noise and the resultant effects of re-radiated noise on and in buildings, today's practical realities can leave a developer exposed to either a deficient (emanating from designers with insufficient knowledge and/or experience) and/or over-conservative / over-complicated and therefore expensive designs (e.g. specifications demanding 3.5Hz coil springs when 8 or 10Hz elas-tomeric bearings will be sufficient or requiring significant amounts of additional concrete). As discussed in a previous paper of this series [1] we believe that it is not realistic and not worth chasing an absolute prediction of required vibration isolation natural frequency down to the decimal place but instead an experienced acoustic consultant with the right equipment and design tools can help to make the first key decision, namely should the building (in part or as a whole) be isolated? Typical answers could be:

1. **No** e.g. The vibration levels are below any criteria set by the local authority and or the level of vibration is not high enough to lead to adverse comment / complaints due to re-radiated noise OR the intended use of the building is not deemed critical enough to justify the additional investment.

2. **No, provided adjustments are made to the design**, e.g. Additional mass and stiffness is added to the foundations OR incorporation of an isolation trench between the source and the building.

3. **Yes**, e.g.
    a. It is the only way to achieve the planning conditions or required performance criteria.
    b. The return on investment can be enhanced by:
        i. Increasing the desirability and sale/lettings value of the development.
        ii. Investing for the long term, e.g. protecting rented and hotel properties from being affected in future from deterioration in the rolling stock and track, increased levels of traffic during the day and or night, the adjacent cinema or nightclub increasing the intensity of their sound systems etc.

c. It is borderline whether structure-borne vibration isolation is required but the project is running on such a tight timescale that there is insufficient time to obtain a definitive answer (that would anyway be caveated with uncertainties) so as part of the risk management approach it may be decided to press on with isolation anyway.

Once the decision is made to isolate then the focus needs to move to the design team (architect, structural engineer, acoustic consultant, building isolation specialist, mechanical and electrical service de-signer etc) where no matter how high calibre they may be, the design development process of a building rarely runs perfectly, not least when there are periods of inactivity as it awaits decisions to be made. Then, once made there is an even greater time pressure to achieve the milestones where all parties are all working in parallel. Best practice should mean;

1. All parties have a clear understanding of what success and failure of a building isolation system means and therein should share the same common goal.
2. The building isolation system is an integral part of the structural and architectural design and should be initiated at the early, concept, stages of design.
3. A creative, collaborative and iterative process where ideas are generated, assessed, discussed and optimised and where details are coordinated and agreed between all parties, ideally using BIM, with compromise required as it may not be feasible to simultaneously meet the requirements of all stakeholders.

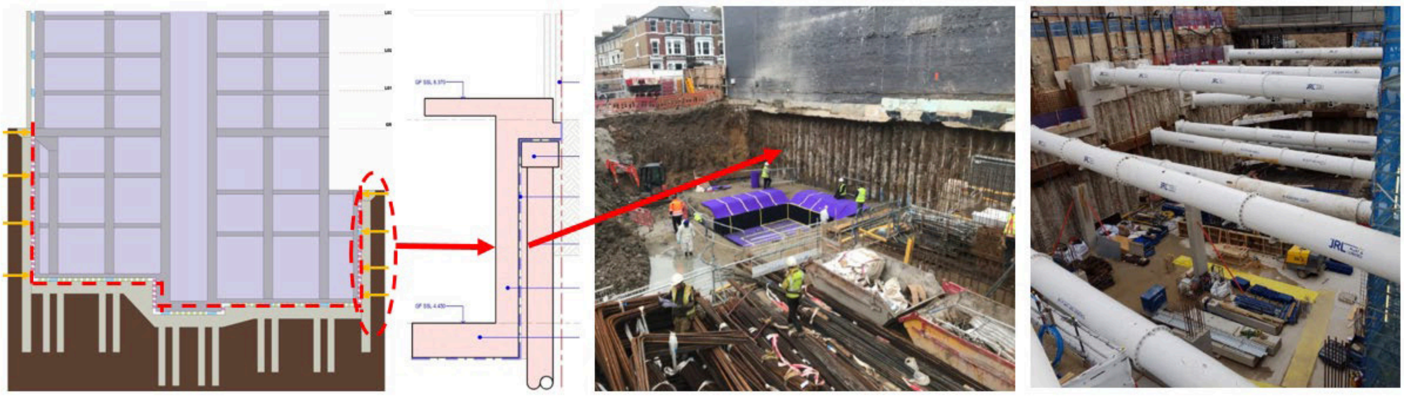
If this is accomplished then a greater return on investment can be realised by making more space available and/or more of the building sold/let to higher value tenants, e.g. or enabling ‘back of house’ areas to become residential, extra hotel rooms or office space etc. It also leads to a more efficient, value engineered building vibration isolation system design.

2. Case studies

The following are examples of where elements of this best practice have been applied and resulted in overcoming significant technical challenges in order to deliver projects on time and budget.

2.1 Complex, multi-level basement structures

There has been an increasing trend over the past decade, especially in mainland Europe, to isolate buildings using full area mats made from either polyurethane foam or recycled rubber. Such systems appeal because of their simplicity but do have their drawbacks, notably when the intention is to construct a deep and or multi-level basement. Consider the example shown in Figure 1a where the red dashed line represents the full area vibration isolation system.



Left to right: Figure 1a: Indicative 'full area' building isolation system for a deep basement, Figure 1b: Acoustically separated double wall (retaining and inner liner) design, Figure 1c: Construction of design shown in Figure 1b, Figure 1d: Example of a deep basement construction.

Potential drawbacks are:

- The high volume (and therefore cost) of vibration isolation material required to line the entire basement and sidewalls.
- The dependency on the stiffness of the ground to achieve the required isolation natural frequency, especially for system natural frequencies below 10Hz [2].
- The orange arrows shown in Figure 1a represent the soil pressure that will act as a permanent force around the perimeter of the building which will act to clamp the building and therefore restrict the performance of the vibration isolation system [3]. For shallow basements it is possible to eliminate this soil pressure by designing the piles in the retaining wall to cantilever but this comes at additional expense as well as a loss of space in the basement. Overcoming this may well involve additional foundation elements to be cast (Figure 1b) adding to the cost and time onto the construction programme and reducing the environmental 'embodied (Graue) energy' credentials of the development through the use of additional concrete.
- The materials are required right at the beginning of the construction programme meaning it may need to be ordered before the contractor is even appointed and installation has to take place in the early, mucky groundworks phase and will likely complicate the construction sequence of the retaining wall and capping beam as well as the waterproofing (Figure 1c).
- The deeper the basement the more challenging this becomes, as implied by the photos shown in Figure 1d.

There are projects where the entire potential of a development, including the number of possible basement levels, is restricted because the perception is that the only vibration isolation option available is a full area mat system. This should not need to be the case, especially since the origins of building isolation use high-capacity elastomeric bearings decoupling the key nodes of the structure along the lines of the examples shown in Figure 2. Such systems can offer a higher level of acoustic performance (system natural frequencies down to ~6 Hz if using elastomeric bearings and, in the rare cases when required, ~3 Hz if using coil springs). They do of course come with their own complexities but through coordinated, pragmatic and thorough design process [1] will result in a system that can fit within the original architectural intent, and be efficient in terms of buildability, programme and cost.

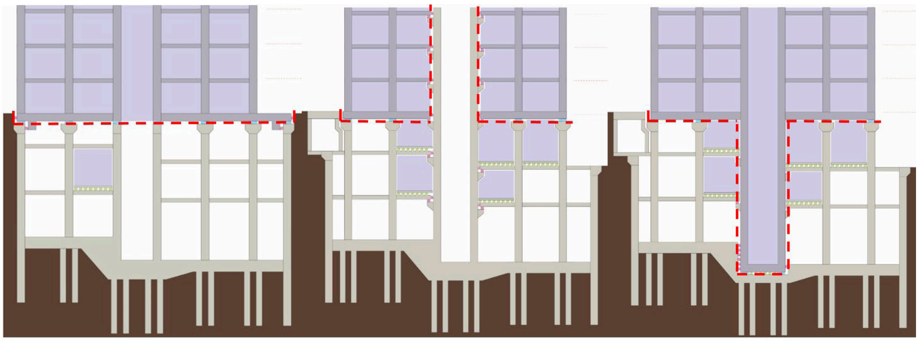


Figure 2: Alternative configurations for building isolation systems incorporated within the building envelope
There are a number of critical design elements that need to be considered and decided upon during the design process such as:

- Where in the building should the isolation line be incorporated, e.g. in basement, below ground floor, below an upper floor?

- Which is more important to the client: plan area and ceiling height or absolute minimal cost?
    - If space is critical then the columns would be expected to have an effective length of x1 meaning they need can be small in plan area but need to be pinned at either end (like an unisolated column) to provide sufficient buckling capacity. This means incorporating vibration isolated lateral restraints into the bearing assembly in order to replicate the pinned effect as shown in Figure 3.

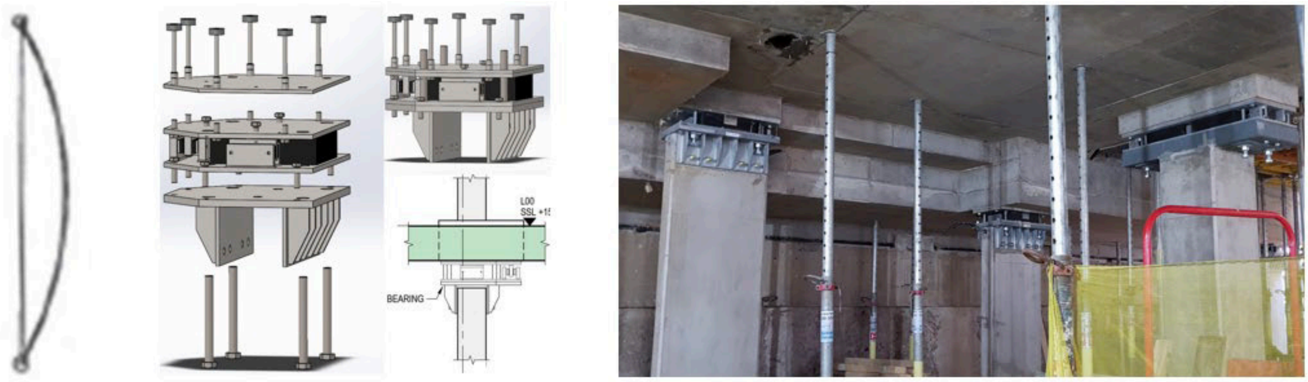


Figure 3: Examples of column bearing assemblies designed with lateral restraints to replicate the 'pinned' effect at the top of columns with effective length of x1, fail safes, vertical continuity ties, compact steel load spreading column heads and a full replacement strategy (for example in case of fire)

    - If space is less critical, for example if the columns are in back of house areas, then the effective length can be increased to x2 meaning the column has sufficient capacity to not need a pinned end. This simplifies and therefore reduces the isolation system cost and ICSV27, Annual Congress of International Institute of Acoustics and Vibration (IIAV), 11-16 July 2021improves its performance by removing additional (lateral restraint) points of contact between the isolated and not-isolated structures.

Ultimately it should be an economic decision to establish if the additional value generated by creating additional plan area and ceiling height outweighs the additional cost of a more complex vibration isolation system design.

Figure 4: Examples of column bearing assemblies designed with no lateral restraints at the top of columns since they have been designed to have an effective length of x2, concrete column heads, fail safes, vertical continuity ties (left but not required in the right hand photo since there was only one basement level) and a partial full replacement strategy (for example in case of fire)

- Does the architectural (and therefore structural) setting out remain consistent up and down the building or are some columns offset? If the latter then this can lead to significant lateral loading either directly across the bearings or that would be transferred into the core. Either case would act to restrict the free movement of the building isolation system and therefore reduce the overall acoustic performance.

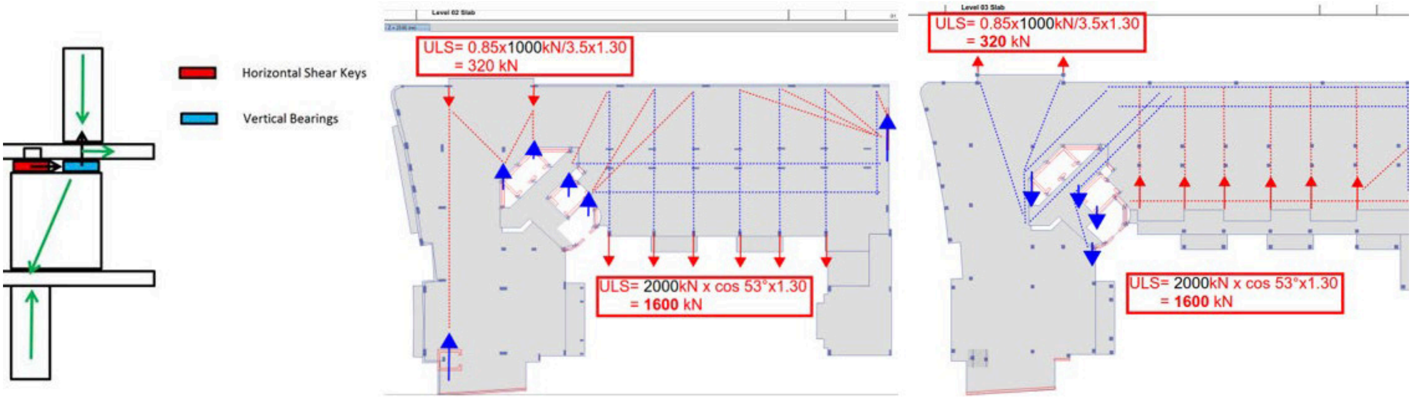


Figure 5: Example showing how offset columns (between 2nd [middle] and 3rd [right] floors) can generate significant lateral loadings that need to be resisted using lateral isolation bearings which, like the perimeter soil pressure example outlined earlier, create a 'clamping' effect that will reduce the overall effectiveness of the building vibration isolation system. (Images courtesy of WSP)

- Examples of other aspects that may need to be considered are:
    - Overall robustness / disproportionate collapse strategy including vertical continuity, fire, blast and vehicle impact protection, fail safes and replacement strategy etc
    - If isolation line is under the ground floor then need to consider the support, isolation and waterproofing around the entire building perimeter
    - Does the basement extend under the entire footprint of the building and what is the planned usage, e.g. does it need to be isolated or not?
    - Interfaces to existing / non-isolated buildings and structures, new and retained facades
    - Fit out and building services detailing
    - Intended construction programme and sequencing including of top down

2.2 Tall buildings (using an example of a 30 storey tower)

According to the UN, 68% of the world population is projected to live in urban areas by 2050 [4]. It is therefore inevitable then that the amount and density of tall buildings will increase. For urban environments to function they need to be connected with public transport and indeed certain funders are only interested in developments constructed near to public transport such as metro/ underground stations. This means that the lower storeys of these buildings may be affected by ground-borne noise from nearby underground rail. That said, as with any building, it is likely to only be the first 4 to 8 floors that would be affected where above that the energy / noise level would drop sufficiently to meet the agreed performance criteria.

By considering the three options shown in Figure 6, the first option (6a) is technically feasible but would likely be prohibitively expensive since the enhancement it would provide would only be valuable for the first 4-6 floors and it would require significant additional structural elements such as outrigger walls as indicated in Figure 7a. The third option (6c) where the lower level floor slabs are isolated from the unisolated columns and core initially seemed like an elegant solution but was eventually rejected because most columns were positioned at the perimeter of the building which meant that they could not rely on the slab wrapping around them to restrain them, i.e. if built like this the columns would effectively be unrestrained for their entire 6 story height. In order to overcome this would require the fabricated shelf angles (as indicatively shown Figure 7c) to be fitted around the internal 3 sides of every column at every isolated level which would be expensive and time consuming to construct and would lead to architectural challenges to fire protect and hide the isolation within the interior fit out.

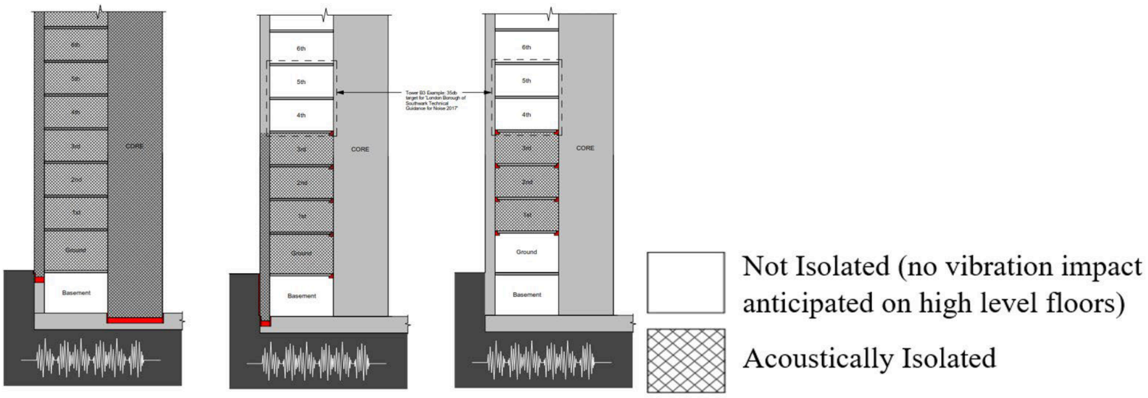


Figure 6: Scenarios considered in a design study to establish the optimal design to protect the first 4-6 floors of a circa 30 storey tower from ground-borne noise generated by underground rail or a basement nightclub. Left, 6a: Full building isolation, Middle, 6b: isolation of columns at ground level and the first 4-6 floor slabs from the core, Right, 6c: isolation of the first 4-6 floors from the unisolated columns and core.

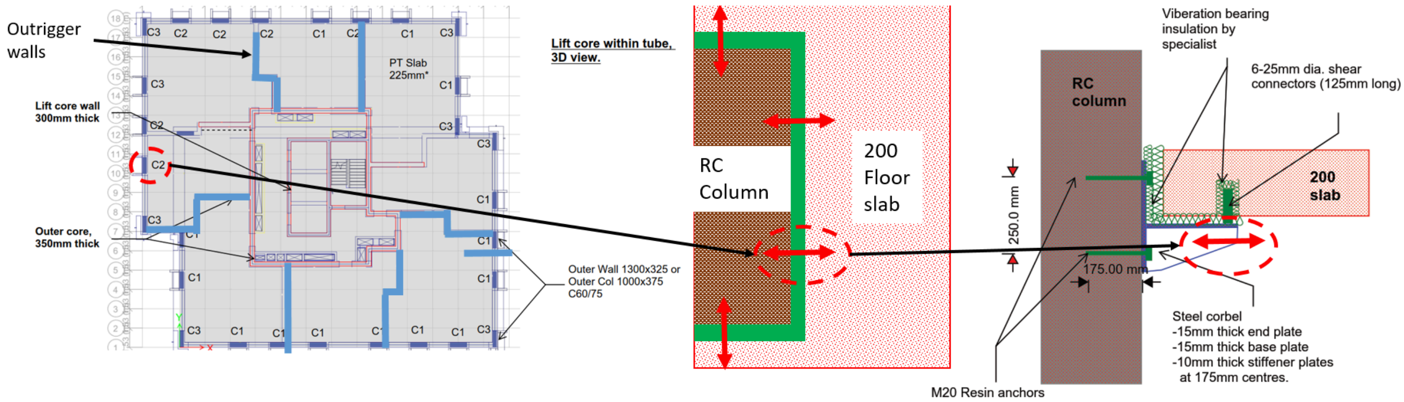


Figure 7: From left, 7a: typical plan of a tall building with the core in the centre and the columns around the outer perimeter, 7b: indicative requirements of the floor slabs providing restraint to the column which would have to be replicated if the column were isolated from the floor slab, 7c: indicative example of a way of achieving the restraint outlined in 7b.

Eventually the decision was made to go for option shown in Figure 6b whereby every column was isolated at the underside of the first floor slab and floor levels 1-6 were decoupled from the core with a simple yet robust vertical support and lateral restraint system all designed for ease of installation.

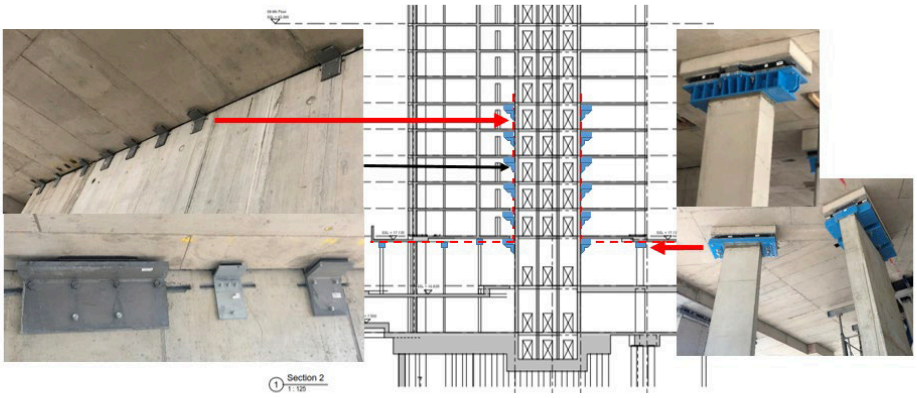


Figure 8: The final, as built solution adopted to isolate the first 6 floors of a 30 storey tower where the col-umns (effective length x1) where isolated at the underside of the first floor slab and the floor slabs of floors 1-6 were isolated from the non-isolated central core.

Now constructed, whilst access into the finished and let/sold apartments within the building was limited, measurements were performed across the isolation bearings to evaluate the performance of Farrat isolation system when subject to external vibrations generated by passing trains and undergrounds. The results presented in Figure 9 show a marked improvement up to 25 Hz and between 40 and 100 Hz. In particular, none of the main disturbing frequencies, located at 2 and 6 Hz, is transmitted to the rest of the structure. This highlights the performance of this type of isolation system and also validates other work [5] justifying the absence of any transmitted resonant peak owing to the huge mass of the building.

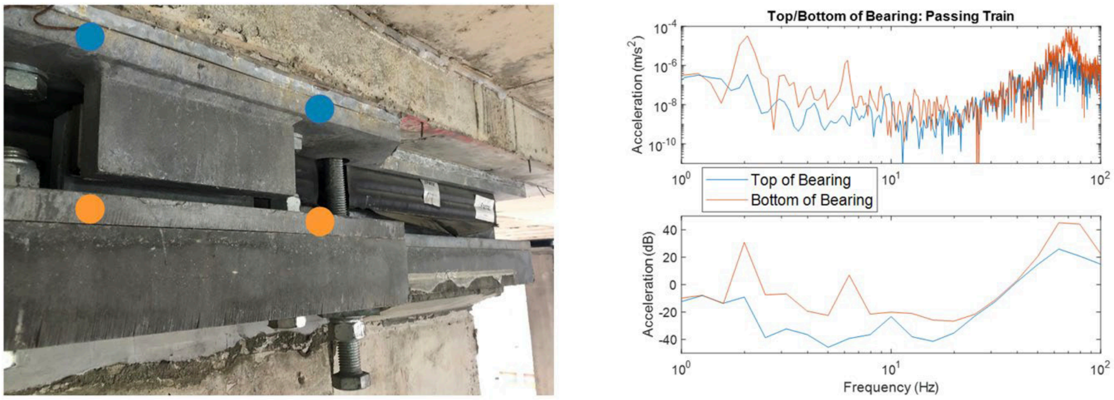


Figure 9: Vibration measurements taken across the (Farrat) bearing assembly that incorporates elastomeric LNR Bearings, fail safes, vertical continuity ties and lateral restraints. A reduction of over 20 dB is shown across the key 40 – 100 Hz range.

2.3 Over station developments

Over Station Developments (OSDs) tend to come with their own distinct challenges mostly around the fact that the building is being built on the roof of another building meaning that the load has to be highly concentrated, often onto a plinth / area that is not idealised. The example shown in Figure 9 is a somewhat extreme example where, even though the station box building was always intended to support an OSD, the designers focussed on cost of the OSD rather than the overall development.

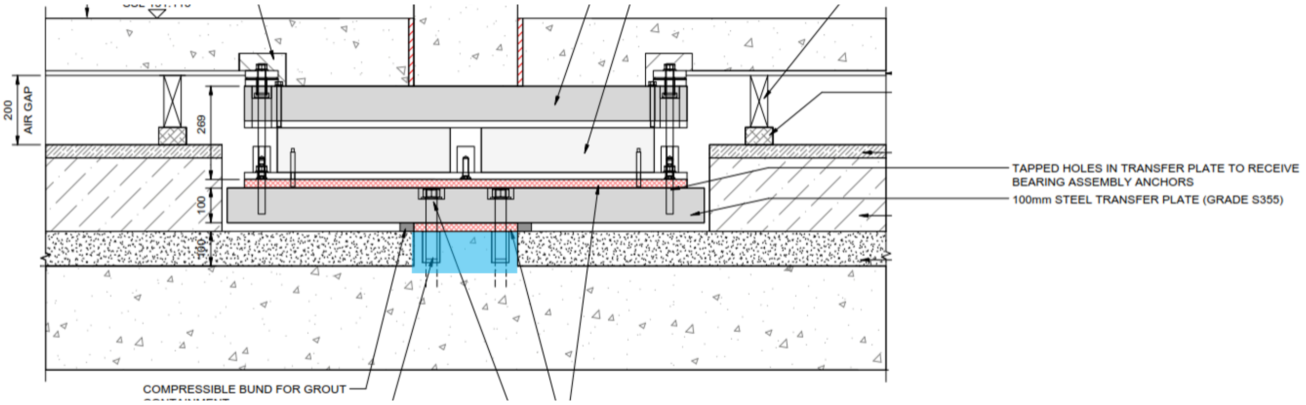


Figure 10: A real world example of the plinth (shown in blue) provided on a station box roof to support the vibration isolation bearing assembly required to support, an as yet unbuilt, 6 storey OSD building. The plinth was limited to the size of the column below with negligible load spread provided by the roof slab.

Despite the ability of the roof structure to carry these concentrated load paths, the depth of an under-ground station building (from foundations to roof) means that the roof will be significantly more flexible than a standard piled foundation which will reduce the overall performance of the vibration isolation system. This flexibility, as outlined in Figure 10, will also vary across the footprint of the OSD meaning that the structural modelling process to align the vertical and shear stiffness of the vibration isolation bearings with the structure is even more critical and may result in the selection of different frequency bearings in order to 'tune' the behaviour of the combined station box, vibration isolation bearing and OSD system in order to find an 'ideal compromise' between structural and acoustic behaviours.

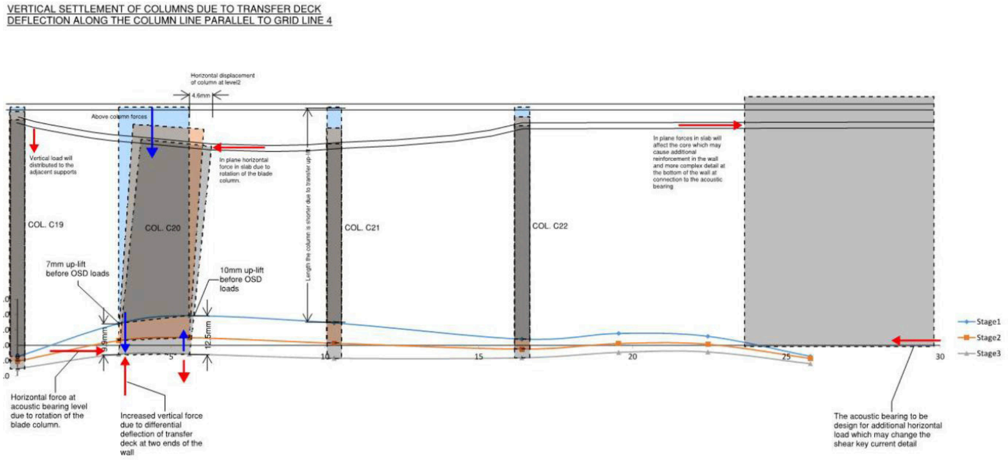


Figure 11: An example of the effects of differential flexibility in foundations (the station box roof) across the site of the OSD building can complicate load paths and generate additional lateral forces that need to be resisted as part of the building isolation system. (Image courtesy of Ramboll)

3. Conclusion

The return on investment potential for a piece of land should not be restricted by the requirement for or design certainty surrounding building vibration isolation systems. Full area mat systems are appealing due to their simplicity but have key drawbacks. Traditional bearing based building vibration isolation systems allow more space to be made available to sell/let at a higher margin and offer more post-design flexibility. These systems, if designed and executed properly, are not more expensive than full area systems and usually lead to a greater return on investment when considered at a whole-site level. Such systems also enable the developer to realise value from complicated over-rail sites. Every building has its own set of challenges, of which this paper has explained a few examples, but by collaboration early in the design programme then significant value can be created for the client.

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