Footbridge Pedestrian Vibration Limits

Part 2: Human Sensitivity

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Summary

The UK Highways Agency has commissioned two companion studies for the review of the dynamic sensitivity of footbridges. The studies examine the dynamic sensitivity from two vantage points. The research reported within this paper and undertaken by Flint & Neill Partnership, is to determine the tolerance of pedestrians to the dynamic motion of footbridges. The second is to assess the sensitivity of different bridge types and to build a database of their responses. The output of the two projects has been combined to produce a basis for codification for the use of bridge designers and assessors.

Keywords: Footbridge; dynamic properties; pedestrian-induced vibrations; natural frequency; damping, analysis.

1. Introduction

This brief for this project was quite-wide ranging and required the re-investigation of all aspects of human user tolerance, acceptance and attitude to induced vibration on footbridge decks. The tasks undertaken included the following:

1. Identification of Forms of Vibration
2. Review of Existing Data
3. Cataloguing of Structural Forms and Response
4. Establishment of Human Response Parameters
5. Field Studies

This paper reports on two particular aspects of the project and provides, (a) some results from pedestrian responses to surveys conducted during bridge excitation tests, and (b) proposals for future codification models. Further details of the background to this project are due to be published elsewhere [1][2][3][4][5]

a) A series of bridges have been tested and users of the bridges interviewed to determine their perception of vibration on the bridge under both ambient and forced vibrations. The interviews also sought to identify the impact of a number of other parameters on user sensitivity such as the height of the bridge, the openness of the parapets, the flow of traffic beneath the bridge and the location of the bridge.

b) Recent changes in expectations for footbridge designs have produced lighter structures that are more responsive to pedestrian actions. In this context, whilst static capacity requirements are easily met, existing dynamic design criteria (particularly in BD37 [6]) have failed to cater for all design selections and certain aspects of pedestrian comfort. This resulted in a concern that current design criteria needed review and possible refinement. In conjunction with the companion study carried out for the Highways Agency, this project has confirmed the need for some changes and has provided a more logical approach to design for response.

   To bridge the gap between more stringent dynamic stability requirements and design freedom, a new methodology is proposed using a more rational dosage-based model of physical discomfort. The loading model has been simplified to apply to an idealised footbridge by the combination of an assumed idealised loading population and discomfort limit curve which provides adjustment for the subject structure's span and principal vertical frequency.

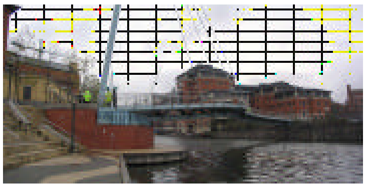
2. Field Studies

2.1 Objectives

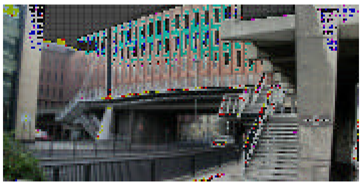
The task is concerned with quantifying users' reactions and attitudes to footbridge movement and, as far as possible, to review the acceptability of the current acceleration-based criteria for design against the findings.

The initial work of this task involved the design of a questionnaire to elicit opinions on a range of bridge design issues, in order to characterise attitudes to bridge movement. The main objective of this project is to determine the degree to which footbridge vibrations give rise to user concerns, and to review the relationship between the vibration limits specified by BD 37/01 and levels at which users experience unease whilst crossing.

Four bridge sites were chosen for testing in the south of England. They were chosen to provide a wide range of structural forms to cover the possible variation in user response issues. The four bridges are shown in Figures 1 to 4.

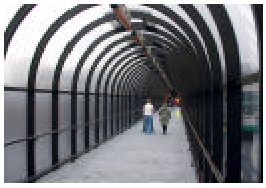


Valentine Cable-Stayed Footbridge, Bristol



Trinity Court Footbridge, London, EC4

Royal Victoria Docks Footbridge



Bromley Footbridge

Figures 1 to 4 – Test bridges

2.1.1 Development of the means of gathering data on user perceptions

Measurements were carried out on the structures by performing a series of both designed and 'natural' forced tests with people providing the forcing inputs. Use of mechanical exciters was considered at the outset, but experience with this type of arrangement suggested that the equipment, which is quite intrusive to a normal footbridge crossing experience, would be likely to distort user perceptions. Furthermore, a greater number of more realistic tests is possible with human forcing, which would have been necessary anyway for collection of the 'natural' or 'ambient' set of responses.

In order to obtain data on the attitudes of pedestrians, a method for recording the users' views was needed. Flint & Neill Partnership had carried out previous bridge surveys where the questionnaires have addressed descriptions of physical sensations and their acceptability for both pre- and post bridge transit attitudes. Interviews of pedestrians on previous projects, for example, revealed that pre-existing attitudes of footbridge users are strongly correlated to their responses after crossing.

2.2 Interviews with Footbridge Users - The Questionnaire

The questionnaire posed questions in a fairly open-ended manner in order to gain a true idea of the relative levels of concern of different topics and to reduce the likelihood that interviewees would be tempted to comment on any issues projected by the interviewers. For this reason, multiple-choice questions were avoided for certain topics. The total sample was not large (421 persons), but the surveys were conducted on a diverse range of bridge forms and situations, each of which was intended to elicit different areas of main concern.

A major objective was to find where footbridge movement as an issue lies as a concern in users' minds compared to other factors, such as height, exposure, security, etc.

<u>Question 2</u> asks whether pedestrians have ever felt uneasy when crossing any footbridge and if so what caused the unease. This is designed to establish a neutral background of *non bridge-specific concerns* and against which answers to Question 3 can be reviewed.

<u>Question 3</u> asks: *"Are there any aspects to this bridge that might cause you to feel uneasy about using it?"*. The results from these questions enable concerns to be reviewed against specific features of the selected bridges, such as parapets and decking as well as movement.

<u>Question 4</u> seeks information on perceptions about trends in footbridge design. People had difficulty with this question, despite improvements to the wording in the second version of the questionnaire. It now seems likely that the problem was more to do with many people's perceptions concerning the design process which were often confused, if the matter had even been thought about at all. The solution was to enter a 'Don't-Know' response if the respondent had no opinion,

or the answer was vague or incoherent.

Question 5 asks about the user's attitude to risk and was designed as a control on different user groups' attitudes to risk; it was considered initially that there might be some correlation to risk attitudes and effects of movement.

Question 6 asked interviewees how much they thought the footbridge had moved when they crossed it compared to any prior expectations.

Further general details of each recipient (gender, estimated age, etc.) were recorded at the finish of each question session by the interviewer to save interviewees' time. It was decided that five to six questions was the greatest number that could reasonably be asked with minimal refusal rates.

By the nature of the questions, there was always a possibility of alarming interviewees. Where such a reaction became apparent, interviewers were instructed to reassure interviewees that the footbridges were perfectly safe!

2.2.1 Treatment of User Perception Results

Fourteen separate user concerns were identified from the surveys . It is open to discussion as to whether some of these categories should be combined or separated. This is an important consideration as there is a potential to misrepresent the weight of concerns as they are grouped in different ways. Notwithstanding the above, a fairly clear set of user perception priorities has been established with bridge deck movement as one concern within the set.

One of the difficulties in interpreting the data lies in the fact that interviews were carried out on or near the bridges. Even in the question on general attitudes to unease (Q.2), factors were mentioned that sometimes seemed to correlate to dominant aspects of the present bridge. The questionnaire attempted to address general and bridge-specific concerns separately, but it is interesting to note that for the bridge with the lowest number of concerns of all (Bromley), the range of concerns expressed for the general (non bridge-specific) case is the widest and therefore possibly least affected by the present footbridge.

2.3 Observations

It should be noted from the outset that it is possible to exaggerate the importance of deductions based on statistics, so only simple interpretations have been placed on the data

Different perceived problems were observed for each of the bridges – in the development of a modern infrastructure, designers are constrained by an increasing gamut of structural, planning, architectural and costing hurdles to achieve the intended purpose of a piece of infrastructure. A number of the structures studied are particularly subject to this process and consequently *user satisfaction* becomes inherently harder to measure and achieve.

Another difficulty with the 'open' question approach is that absolute levels of a given concern type are likely to be reflected inconsistently if it is only, say, the third greatest concern an individual has and therefore might not be mentioned.

2.3.1 Non bridge-specific Concerns

The answers to question 2 were intended to elicit views on non bridge-specific concerns. The averaged concerns exceeding 2% were reflected in the results as follows:

1	Movement	7%
2	Height of Deck	6%
3=	Feeling of Exposure	3%
	Decking opacity / security	3%

It is interesting to note that a wide variety of issues were expressed, (15 concerns being recorded), with no single issue being strongly dominant.

2.3.2 Perception of changes in tendency for movement in footbridge design

As has been shown above, absolute concern over movement is low; in addition, a comparison of perceived levels of movement with concerns over tendencies for movement in footbridge design (answers to the second part of question 4) produces an interesting result: The bridges where users felt the least concern for tendencies for movement in design were Trinity (the most mobile and where most concern was expressed over bridge-specific movement) and Gaol Ferry suspension bridge, where 50% noticed a small amount of movement. This, coupled with a small number of comments stating faith in the abilities of designers, should provide a measure of comfort to footbridge design engineers.

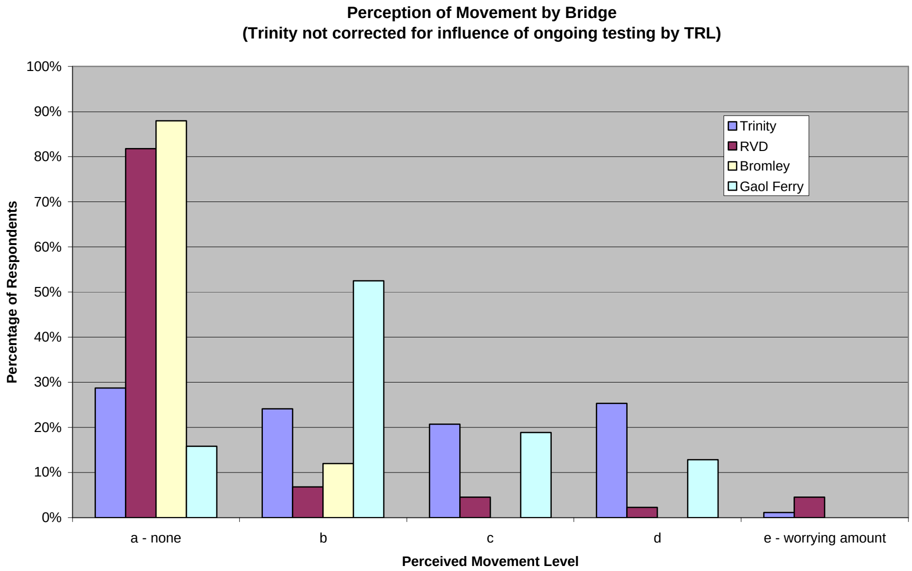


Figure 5 - Footbridge user movement perceptions

2.3.3 Self-Selection of Interviewed Population

Unfortunately, it is inevitable that the proportion of users unhappy with crossing the selected footbridges and that avoid doing so will be under-represented in a study where interviews are conducted on or near to the bridges. A study to address this was mooted involving off-structure interviewing on alternative adjacent routes, but this was not pursued as suitable alternative routes were not close enough to the footbridges in question to be helpful.

It will also be noted that a very small proportion (1%) of users were not fully able-bodied and therefore their views will not have been gathered as a true proportion of the general population.

The age distribution of interviewees for all sites showed a heavy bias of users between the ages of 20 to 55.

Selection of bridges for interviewing was primarily predicated on bridge form and design for particular reasons. The self-selecting effect that this may have on other aspects such as the social class (and therefore possibly attitude) of bridge users living or working in areas adjacent to such bridges has not been accounted for.

2.3.4 Attitudes to Risk

Figure 6 shows the break down of interviewees' general attitude towards taking risk. It can be seen that there are no particularly surprising variations between the results from each bridge, indicating that this aspect is probably not skewing the findings.

2.4 Discussion

2.4.1 Discussion of Interview Results

The survey statistics show that concern over footbridge movement was cited for 5 to 10% of footbridge users and may be slightly greater than other concerns where no other dominant source of unease exists.

Interviewers reported that the strongest feelings of interviewees centred on issues such as height and exposure, whereas movement concern seemed rarely to be a source of significant worry. As stated previously, the interviewers' signs included the phrase "Attitudes to Footbridge Movement", which could have increased interviewees' predisposition to raise the issue of movement where nothing else sprang immediately to mind.

The interview methodology was intentionally unconstrained in order to admit un-thought of reactions for consideration, but this in turn means that answers to more specific questions that might have been posed using multiple choice are not available.

Comparison of such concerns as movement and concern over changes in the tendency for movement in footbridges indicate a seemingly balanced set of opinions from the limited subset of persons interviewed.

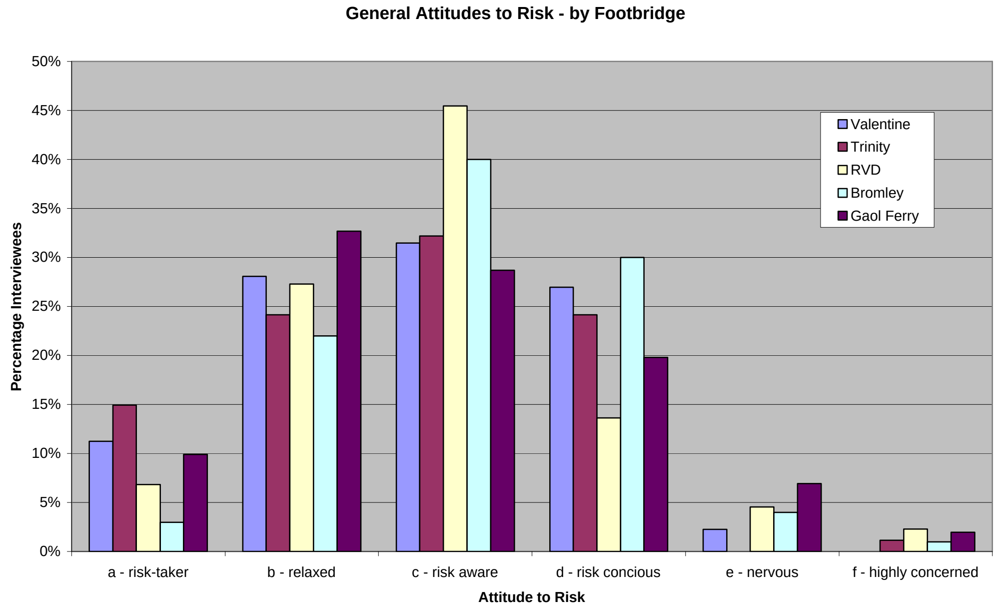


Figure 6 - Distribution of Attitudes to Risk of all interviewees

Of the bridges tested, Trinity is the liveliest and is an interesting case for review of permissible response thresholds. In addition, when the structure was intentionally excited by forced response, there was a demonstrable associated increase in the concern of the interviewees regarding movement of the bridge. This footbridge was perceived as 'mobile' despite factoring to remove the effect of pedestrians witnessing the forced testing.

2.4.2 Extraction of Key Design Parameters

Analysis of data from the field studies has shown that bridge movement remains a concern for users, possibly the greatest concern, but not significantly so. It was clear that there was correlation between the perception of movement and the actual level of movement exhibited by the bridge. One of the bridges tested showed vibration levels arising from the action of one pedestrian to be greater than the limits in BD37/01 (walking at resonance). Analysis of data showed that relative to the BD37/01 threshold, as many as 10 to 20% of bridge users experienced higher than expected levels of movement. However, this does not necessarily mean they were unacceptable. The number of users experiencing 'worrying levels' of movement was always below 5% and it is possible that even this figure (Royal Victoria Docks) was increased by psychological factors such as exposure - it is actually a relatively unresponsive deck at walking frequencies. From this, it may be fairly concluded that the BD37/01 threshold is set at an appropriate level for single walker excitation.

It should be emphasised that the above is based on a small data set with a large number of uncontrolled and potentially contributory variables.

The responses obtained from pedestrians in the trials showed a large number of concerns related to footbridges, but only a few of these related directly to their perception of movement. The clearest point that emerged was the height of the bridge deck above the surrounding terrain affected the responses of a proportion of users.

Clear patterns emerged in the dislike of open parapets and flooring where users were uneasy at having a lack of enclosure around their person. A feeling of protection increasing users' acceptance of bridge motion was highlighted in the tests on Gaol Ferry Bridge with its heavy-looking parapets. Quantification of the beneficial effects will be difficult; however it is proposed that the increased sensitivity to open or lower parapets as well as deck height should be developed into a codified method.

No direct evidence was obtained from users who sought to avoid crossing the bridge as it was difficult to identify interviewees who might be thus affected. However, it is proposed to take the criterion of route redundancy through to codification as some questionnaire responses did indicate that the unease at footbridge movement would prompt some of the most sensitive pedestrians to avoid the structure.

2.4.3 Consideration of Disability and Human Tolerance Issues

A fundamental limitation of all previous studies aimed at guiding the design of footbridges' response is that comfort criteria have been derived from a largely able-bodied walking population. This has not properly taken into account the discomfort of disabled, slower or elderly/infirm users or any consequential tendency this has on discouraging their use of footbridges. It will also be noted that the proportion of elderly in the population is increasing, as is their influence.

In fixing upon an approach to incorporating human tolerance issues within the design process, it has become clear that, although changes in disability/infirmity awareness have modified footbridge design attitudes with respect to physical aspects such as accessibility, the psychological effects of height and movement on a minority of the stakeholding population have not.

An important question to be posed is the degree to which the needs of such persons should be accommodated in the design scope, through which they may well define the limits for permissible footbridge response.

Such a design philosophy will inevitably lead to greater restraints on design; whether or not these restraints are seen as limitations or a challenge to build something better is part of a wider discussion for the design community to address. There is certainly merit in considering the response of structures where disabled or reduced-capacity walkers need access across a footbridge. The most likely case in point will be access to hospitals or care facilities.

2.4.4 Other Observations

On three of the structures reviewed, it was noted that stairway ramps were responsible for triggering a great deal of the movement felt on deck. This is probably because of the way in which brisk walkers descend those parts of the structure (energetically and rhythmically). The way in which such walkways are designed and attached to the main deck and thereby transfer that energy is therefore a matter for dynamic design consideration.

2.5 Proposals for future codification

It is considered that an approach similar to those outlined in BS 6472 [7] and ISO 2631 [8] is most appropriate for future use with footbridges, where,

- A single motion sensitivity curve will be used that can simply be factored to suit different circumstances and design conditions.
- The sensitivity curve (Figure 7) will be presented in the form of frequency weighting so that responses at varying frequencies can be combined to give a single effective response. (It might be useful to provide weighting factors that give an effective response at 2Hz, the standard walking frequency, instead of the 1Hz used above.)
- A vibration dose time-dependency rule could be adopted (such as that suggested in BS 6472) as the means to compare the nuisance (comfort) level of bridges with different patterns of loading and varying dynamic properties.

Comfort criteria based on the above would provide a sensible method by which bridges with quite disparate properties can be compared. Such a method could also integrate the net discomfort effect over frequencies and time (duration) to compare responsiveness to standard load models.

Given that the intrinsic need to assess the performance of bridges over a range of frequencies is more relevant to the subject of dynamic bridge behaviour, the derivation of the pedestrian input loading is undertaken in the companion study.

3. Derivation of Codification

3.1 Introduction

The data sets obtained from the field tests have confirmed which of the site specific constraints identified through the earlier studies are likely to modify users' perception to vibration. These modifying perceptions have been taken forwards and proposals made to provide a quantitative means of assessment.

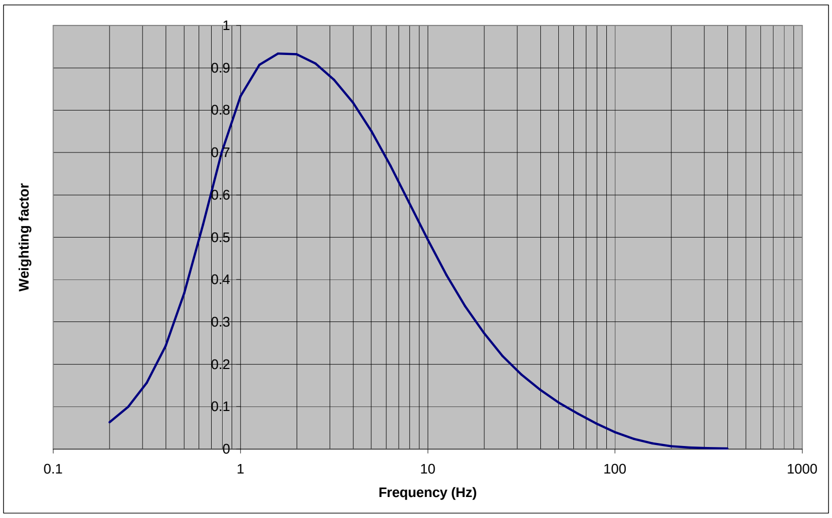


Figure 7: ISO 2631-2 frequency weighting factors

It must be recognised that the quantification of such a subjective criterion, the sensitivity to vibration, can only ever be approximate. The data collected form a starting basis for this assessment but there is no doubt that more data will need to be collected in due course to confirm the findings of this study. We may also see changes in public perceptions with an increasing recognition that structures are not necessarily static and that dynamic behaviour should not be equated with a loss of safety (this was borne out to some extent by a number of informal comments made during footbridge user interviews). Conversely, a well publicised bridge failure (not necessarily in the UK) could result in a loss of user confidence, thus driving down acceptance levels for vibration.

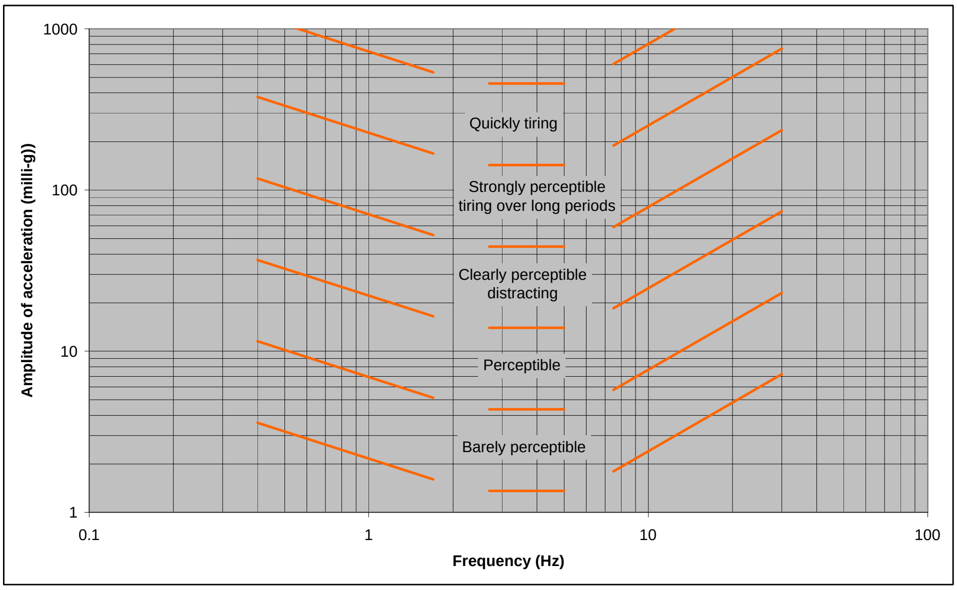


Figure 8: Qualitative description of human reaction to sustained steady oscillation

Among the background data available on the perception of pedestrians to vertical vibrations, one figure in particular is worthy of reproduction. Figure 8 above is taken from 'Wyatt T.A.W.; Design guide on the Vibration of Floors; 1989' [9] and indicates the relative importance of vibrations of different amplitudes. Very sensibly the lines are deliberately left vague and have an unfinished appearance in keeping with the very subjective nature of such perceptions. It is evident from the logarithmic amplitude scale that small changes made to code sensitivity limits can have only a marginal effect on perception.

3.2 Codification Methodology

The basic proposal for the method of assessment of vibration on footbridges follows the basis laid down in ISO 2631-2: 2003 : Part 2 for the use of acceleration doses, as outlined in the companion paper and developed numerically in the companion study. In summary, the approach considers the acceleration dosage to be the most important parameter, *i.e.* what is felt by a user on the bridge over the time of the user's presence on the bridge.

The bridge is classified on the basis of its usage classification and the net response calculated and scaled back as a relative response compared to that of an equivalent standard bridge. The standard bridge is assumed to be a 50 metre long, 2 metre wide footbridge with a first mode of vertical vibration at a frequency of 2 Hz. The standard bridge is assumed to have a logarithmic decrement of damping of 0.03. This provides the designer with a scale of relative bridge 'liveliness'.

The bridge response is checked against a single frequency value at 2 Hz based on a classification system of user tolerance and site specific criteria.

3.3 Proposed Codification

It is proposed to retain a value similar to the current standard for acceptable vibrations as a base level, and to factor this up and down in recognition of the need to provide the designer and owner the means to modify the response of the bridge for site specific and user sensitivity criteria. Two proposals have been considered.

1. The first is to use a single acceleration limit and to modify it by site-specific multipliers, including user sensitivity.
2. The second is to use a series of acceptance levels that will depend primarily on the nature of user sensitivity for the structure. Note that this is distinct from the number of users of the structure which is taken into account separately within the loading model.

<u>Proposal One</u>

The basic acceleration limit shall be 1.0 m/sec^2. This is slightly higher that the current BD37/01 limit at 2Hz (the significance of the frequency is that it matches that of the 'standard' bridge). It is also numerically convenient that it is unity, making the acceleration the product of the modifying factors. Thus the limiting acceleration is calculated as follows:

$$a_{limit} = 1.0.k_1.k_2.k_3.k_4 \quad (1)$$

Where

k_1 = site usage factor

k_2 = route redundancy factor

k_3 = height of structure factor

k_4 = exposure design factor

k_1, k_2 and k_3 are taken from the Figure 9.

k_4 shall be taken as 1.0 unless otherwise agreed between the designer and the overseeing authority. Through such a agreement a value of between 0.8 and 1.2 may be taken to reflect other conditions that may affect the users' perception towards vibration. These will include consideration of parapet design height/solidity/opacity, quality of walking surface/solidity/opacity and provision of other comfort-enhancing features.

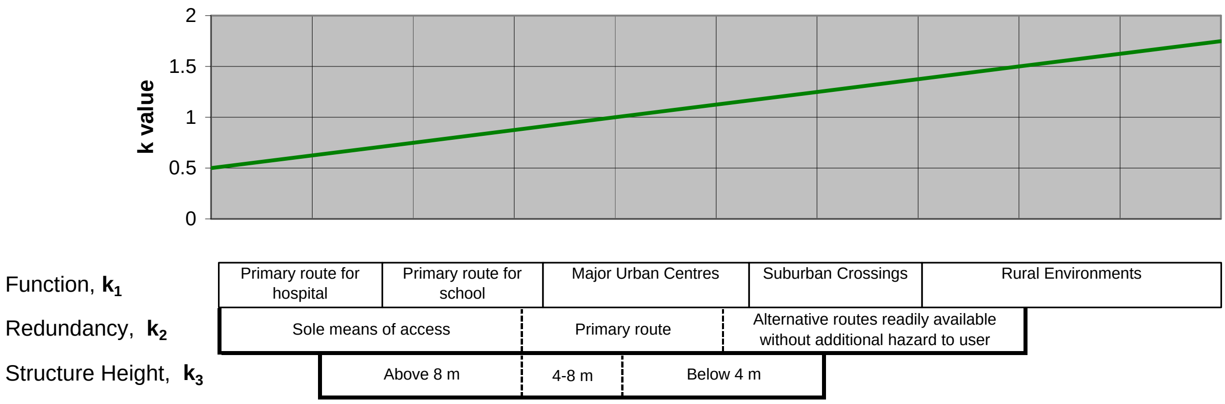


Figure 8 - Proposed response modifiers

Factor k_1 reflects the user sensitivity at the site. Here the desire is expressed to reduce response for more critical sites such as near hospitals or schools. A sliding scale is used to reflect the increasing tolerance of motion with less critical structures, reflecting the lower usage of the structure and the increasing able-bodied nature of users in a rural or remote environment where the bridge can only be accessed by a long walk or bicycle ride. There is some duplication between this factor and the usage criterion embodied in the loading model.

Factor k_2 takes into account the route redundancy of the structure, requiring a lower level of response where users have no alternative but to use the structure. Care needs to be taken in providing codified guidance on this as the determination of route redundancy may not be well understood.

It is intended that the redundancy relates to the primary means of access to a particular feature, thus a sports stadium with a footbridge that leads to a railway station and provides the primary access for visiting fans would attract the lowest acceleration limit. Conversely, a footbridge in a rural setting providing one of several means of access into a country park should not attract the same stringent requirements, and a higher acceleration may be used.

Factor k_3 reflects the greater unease associated with increasing height above the surrounding terrain. Bridge heights between 4 and 8 metres mean clearance are given a neutral value of unity (*i.e.* they do not modify other factors). For heights greater than 8 metres consideration should be given to decreasing the limiting acceleration to reflect the increasing unease. For structures closer to the ground a higher value of acceleration could be used to reflect the greater security that proximity to the ground provides.

It should be noted, when taking into consideration the use of a higher factor for lower structures, the data on effect of height are skewed towards the taller structures, with little confirmation that users find lower structures more comfortable (i.e. they just find higher ones less comfortable). Justification of this increase can only be made on the basis that it is intuitive that the increase is appropriate. The height should be taken as an average height over the central half of the bridge.

k_4 provides the means to account for other features of the design that will alter the user's perception to vibration, and is therefore the most problematic factor. It is intended that the factor should be used to modify the acceleration limits for any other site specific design features that are non-standard. Examples of this include very low solidity or fully glazed parapets where a pedestrian's phobic reactions might be heightened by vibration. A factor of 0.8 is recommended in this instance. Similarly, open grating decking where the pedestrian has a direct frame of reference of the moving deck with stationary features below would also require a reduction in response by 20%.

Proposal Two

The second proposal recognises that the primary function of the bridge should be the dominant criterion and draws this to the fore. In this case, the issues of route redundancy and height follow as secondary parameters, scaling the basic response as in proposal one. It is worth noting that the acceptance levels as described provide a degree of cross -over with the redundancy factor and that the two could be combined into one factor. The basic levels of response are proposed as follows:

Acceptance Level	Criteria	Upper Limit (ms^{-2})
Minimum	Routes to essential facilities, such as access to hospitals and schools where users may have impaired mobility	0.5
Median	Standard for bridges in an urban environment	1.0
High	Rural Setting where usage is generally low	2.0

The limits may be modified by agreement between the designer and owner for site specific factors such as height of structure above ground level, bridge parapet and deck porosity.

3.4 Commentary

The two methods proposed provide contrasting methods of assessment. The first method attempts to provide much greater flexibility to the designer to make a critical assessment of the site and its usage. This enables a more focused response to all the parameters that have been found to affect pedestrians' tolerance to footbridge vibration.

The second method provides a limited degree of variation to reflect only the particular needs of bridge users. It is banded into distinct classes and forces the designer to select a specific value of acceleration. Some modification for site specific criteria may be made; more detailed provisions could be provided if deemed appropriate. The final decision on certain aspects of codification will depend on the output from the companion study if the excitation levels may vary more significantly than the comfort levels.

It is clear that a short description will be required to accompany these code clauses to describe the usage of the classes of structure and which sites might require a higher or lower limiting level of acceleration. Delineation between sites that might carry the occasional mobility impaired pedestrian and those outside hospitals will be needed. No evidence has emerged of user complaints from mobility impaired pedestrians; it is suspected that the climb up and over a typical urban footbridge would dissuade many less able pedestrians.

4. Conclusions

4.1 Subjective nature

In conjunction with its companion study *"Footbridge Dynamic Response Properties and Measurement",* this project attempts to provided a well-grounded and more reliable approach to designing for the response of footbridges, particularly modern lightweight structures.

The discussion identifies the need for a simplified yet customised approach to the dynamic design of footbridges.

Prior research has always stopped at addressing only the easily quantifiable. But if design flexibility is to be maintained, subjective aspects of design should also be incorporated into the design process.

4.2 Recommendations for Further Development

Human tolerance, particularly psychological, aspects are difficult to include within the design process, but a system of modification factors is proposed to cater for this. Aspects of these factors may require further modification in due course as a greater pool of data becomes available, however, the current proposals are considered to provide an appropriate and justifiable starting point. Simplification of the modification (k-) factors is possible, though the cited factor k_4 which attempts to provide weightings for different aspects of the bridge detailed design that may affect user psychological comfort, requires further development to be practical. (As presented, it allows the client to arbitrarily increase or decrease the service level requirement.)

Consideration of how to build up and apply the k factors in practice is required to cater for specific cases, *e.g.* where a footbridge consists of two types of decking or parapet that attract different weightings. The structuring of any standard has to allow for such possibilities.

Further thought is also needed on the matter of whom to design for. Consideration of environmental and societal factors should inform decisions on the levels of disability or phobic predisposition in the user to be accommodated. A consideration of the needs of seated users has not been undertaken; requirements are likely to be heavily skewed by bridge specific requirements.

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