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PRACTICAL CONSIDERATIONS IN THE ASSESSMENT OF BUILDING MOTION ACCEPTABILITY

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ABSTRACT

Wind-induced accelerations and associated occupant comfort considerations are governing factors in the design of a significant number of tall buildings. However, the various criteria that are used to assess the acceptability of these motions have been derived from a number of different experiences and approaches. This paper re-examines these in light of examples of field experiences of motion perception and acceptability and proposes alternative approaches to be used. The alternative approaches take into account not only the published criteria, but also local and building-specific factors including local wind climate, occupant expectation, and likely occupant response. A basis for providing recommendations to clients on suitable acceleration guidelines will be presented. Methods of acceleration mitigation will be briefly described within the contexts in which they might be successfully employed.

KEYWORDS

Tall buildings, motion perception, occupant tolerance, serviceability accelerations, acceleration guidelines.

INTRODUCTION

Excessive motion of tall buildings during wind events can lead to occupant dissatisfaction with building performance. The role of the tall building designer is to ensure that this motion, most often expressed in terms of serviceability accelerations, is limited to a level where the occupant dissatisfaction is limited to a level that is acceptable to the building owners or managers. This is normally conducted through analytical or wind tunnel estimates of the expected accelerations and comparison of these accelerations to published guidelines. However, current guidelines do not take into account all the factors that should be considered in design. One of the difficulties in selecting appropriate guidelines is that very few designers understand the basis of current design guidelines, or the other factors that will affect occupant satisfaction or dissatisfaction with perceptible motions in buildings. Part of the lack of knowledge is that field experiences can rarely be published, as unacceptable motion environments most often provide the platform for confidential litigation. However, as serviceability accelerations can often be a governing criterion in design, it is important that designers more fully understand the goals of design guidelines and how they might be modified for different buildings.

CURRENT MOTION GUIDELINES

There are a number of different motion guidelines in use by tall buildings around the world. These have been developed by completely different approaches and it is worth reviewing these to fully comprehend how comparable they are. Accelerations are expressed in a range of units including the SI m/s^2, milli-g (thousandths of the acceleration due to gravity, 1 milli-g = 0.00981 m/s^2), and gal (galileo units, 1 gal = 0.01 m/s^2).

NBCC

The National Building Code of Canada guidelines are among the oldest and the most straightforward. These give a wide range of acceptable peak accelerations based on a ten year return period. The range provided is from 10 milli-g to 30 milli-g, with the suggestion that the lower end of the range is more suitable for residential buildings with the upper end more suitable for commercial (or office) buildings. The exact reasoning behind this suggestion is not known, but relevant considerations may have included (a) residential buildings are occupied for more hours of the day than office buildings, and occupants are therefore more likely to experience randomly occurring high-wind events; (b) persons are less sensitive to motion when at work than when at leisure; (c) people are more forgiving of their work environment than of their own personal home; (d) occupancy turnover rates are higher in office buildings than in residential buildings; and (e) office buildings are more conveniently evacuated during extreme-motion events. Typically, recommendations are made to limit accelerations to some values in the 15 to 25 milli-g range, and a number of variations of them have been published in following years (e.g. Isyumov, 1995). The NBCC guidelines, and derivatives thereof, have no frequency dependence.

One reason commonly given for the continued use of the NBCC guidelines, and arbitrary 'standard' values derived from them, is that many buildings have been designed using these guidelines without any subsequent complaint. Thus, the argument for the validity of these guidelines is that when wind tunnel test results suggest that a building will comply with the guidelines, the field accelerations will be acceptable.

HONG KONG AND CHINA

The most recent versions of Hong Kong structural design codes (Code of Practice for Structural Use of Concrete, 2004) use much more prescriptive acceleration criteria. These were adopted directly from the Chinese design code (JGJ 3-2010). Again, the return period used is 10 years with criteria of 0.25 m/s^2 peak acceleration for office buildings and 0.15 m/s^2 for residential buildings. The basis of these is believed to be the midpoint of the upper and lower ends of the NBCC criteria.

ISO6897:1984/BS6611:1985

ISO6897 was published in 1984 and subsequently republished as British Standard BS6611:1985. There are two graphs: one for perception thresholds; and one for recommended limits. While the perception threshold graph was developed with the aid of laboratory experiments on motion perception, the graph on guidelines was developed with a primary reliance on field data (Irwin, 1999). In this case, the field data came from measurements in a wide range of eighty structures of different occupancies and uses. In some, there had been complaints about the motion while in others there had been no complaint, despite motion having been perceived in a number of these. An examination of the original field data does not show any clear trends with regards to significantly different responses to the motions depending on the type of structure. For this reason, there is no differentiation in ISO6897 between residential and commercial buildings, with only one curve for both types of occupied structure and a separate curve for offshore fixed structures. The acceleration guidelines are given for a root-mean-square (r.m.s.) acceleration over a 10 minute period with a return period of 5 years. The biggest difference from the NBCC guidelines, though, is the incorporation of frequency dependence with more stringent requirements for higher frequencies which were found to be more readily perceptible.

ISO10137:2007

This more recent ISO standard, published in 2007, retains the frequency dependence of ISO6897, but moves to a peak acceleration basis with a return period of one year. The one year return period brings this ISO standard into line with Japanese guidelines. Separate recommendations are given for office and residential buildings. While the office building recommendations are broadly similar, when adjusted for return period, to the recommendations of ISO6897, the residential requirements are significantly more stringent. The rationale for this change, beyond harmonizing with more traditional approaches, is not clear.

AIJ

The Architectural Institute of Japan has published guidelines that are very different from the others. They are presented as a series of peak acceleration perception curves. These are presented as average thresholds of perception of 90, 70, 50, 30, and 10% of the population and are largely based on motion simulator experiments. The guidelines then allow the design team to select what percentage of the population they are comfortable with perceiving the motion on an annual basis. It is, therefore, an approach that puts the onus back on the design and client team to assess what level of perception the team is willing to accept, and it is implied that lower levels of perceived acceleration will be correlated with lower levels of dissatisfaction.

FIELD EXPERIENCES

Gaining reliable information about field experience of occupant reaction to wind-induced motion is difficult. In the cases where there are problems, it is rare that data can be published on the reactions to the motion and even that the motion leading to complaints can be quantified. Where access has been given to building occupants following major wind storms, the responses are often biased by the fact that queries are being asked immediately after a storm that may already have elicited comments from the occupants. The first author is one of the few researchers to have had access to a number of “lively” structures over the course of several years during which the occupants were given self-reporting mechanisms and were also interviewed on very recent experience under a full range of wind conditions. In this way, the act of interviewing was not a cue to report that perceptible motion had been experienced or that an occupant was dissatisfied with the motion. The two primary structures that were instrumented to measure accelerations and record occupant reaction were the Brisbane and Sydney Air Traffic Control Towers (ATCTs), as shown in Figure 1. Sydney ATCT was the location of all of the interviews and of an extensive exit interview at the end of the study. One further tower, the Port Operations and Communications Centre (POCC) in Sydney, was used for cognitive performance testing and interviews on the motion experience were conducted with the subjects.

(a) Brisbane (b) Sydney (c) POCC

Figure 1 Control towers used in study

Brisbane ATCT has a natural frequency of vibration of 0.54 Hz and had been occupied for around 7 years prior to the start of the studies, while the Sydney ATCT, with a natural frequency of 0.95 Hz had been newly built, and the controllers had immediately expressed concern about the perceptible motion. The POCC used naïve subjects who did not normally occupy the tower and it had a natural frequency of 0.39 Hz.

Perception Thresholds

From the interviews and self-reporting of motion, it was possible to calculate the average thresholds of perception of motion in each of the towers. The long-term survey data from Sydney ATCT is shown in Figure 2 in terms of the peak acceleration. It also shows the ratings used in the interview from barely perceptible to disturbing/frightening/nauseating. The numbers at the top of each bar indicate the number of surveys conducted in each acceleration band. Figure 2 shows an average threshold of perception of peak acceleration of around 2.5 milli-g.

The perception thresholds from the three towers were found to show clear frequency dependence. When the standard deviation (often referred to in guidelines as root-mean-square or r.m.s.) accelerations were compared with those in the average perception threshold curves of ISO6897, they were found to be radically lower. However, recognizing that the ISO6897 perception thresholds had been derived from simulator experiments using sinusoidal motion when the peak accelerations measured from the field experiments were compared with the ISO values multiplied by $\sqrt{2}$, then the agreement was found to be good. This illustrates the importance of the peak accelerations in triggering kinaesthetic motion perception.

The agreement between the field and laboratory data with regards to perception is interesting, as they are two very different environments. In the laboratory, in most cases, participants are aware that they are taking part in experiments and would thus be expected to be more sensitized to the motion due to the anticipation and expectation involved. In the field, however, occupants need to be distracted sufficiently from their primary task by the motion to register the fact of the occurrence of the motion. In this way, the field data is more of a ‘distraction’ than a ‘perception’ threshold. Intuitively, on this basis, it would be expected that the average perception threshold in the field would be higher than in the laboratory environment. Countering this is the influence of motion cues other than kinaesthetic cues, such as visual and auditory cues.

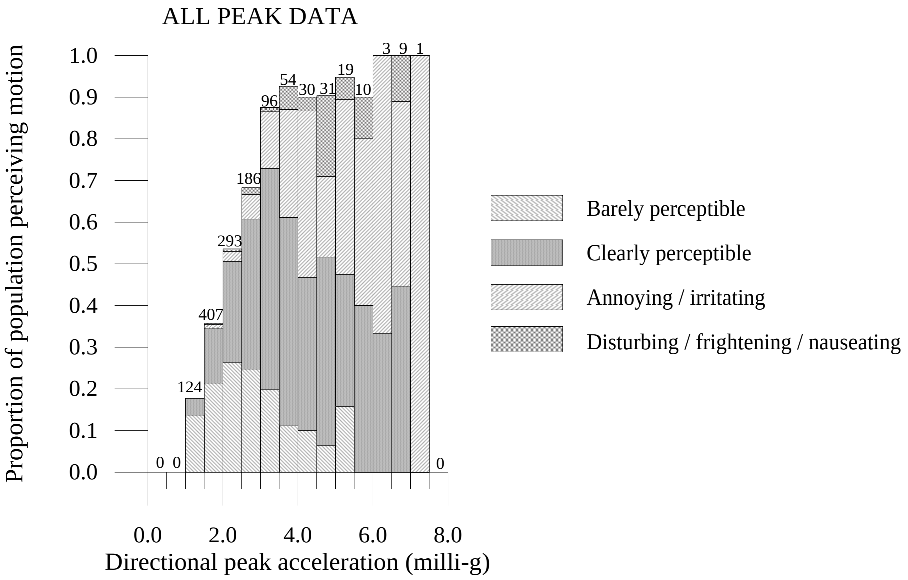

Figure 2 Survey perception data from Sydney ATCT

Visual cues tend to be internal in nature and include swinging lamps and/or blinds, movement of liquid surfaces, etc. There are also parallax cues when the motion is sufficient to cause an occupant to sway slightly in response to the motion. Here, the apparent relative motion between objects at different distances from the observer serves as a motion cue. This is the most likely cause of regular reports of buildings swaying visibly when reported by observers inside the building. Auditory cues can also occur such as doors that are swinging and making a creaking noise, or venetian blinds clinking against window frames. Another key audible cue is other building occupants mentioning that they can feel the building move, thus providing the distraction that results in other occupants perceiving the motion.

Wind Climate and Building Response Characteristics

The acceleration and wind speed data gathered from the Sydney and Brisbane ATCTs were used to extrapolate out to predicted 5-year return period r.m.s. accelerations for comparison with ISO6897 recommendations. Field data from an earlier long-term study of the response characteristics of the POCC was also used to extrapolate data. A summary of the response characteristics is given below in Table 1.

Table 1 Summary of response characteristics and occupant reaction for three control towers

Location	Predicted 5 yr return period r.m.s. acceleration (milli-g)	ISO6897-1984 5 yr return period r.m.s. acceleration criterion (milli-g)	Hours/year perceptible acceleration	Days/year perceptible acceleration	Complaints	Storm type
Brisbane ATCT	3.24	3.43	30	20	No	Thunderstorms
Sydney ATCT	2.75	2.73	705	185	Yes	Gales
POCC	9.25	3.90	897	187	No data	Gales

It can be seen that Brisbane and Sydney ATCT perform very similarly in relation to the guidelines of ISO6897. However, there is a huge difference in the number of occurrences of perceptible motion each year. In this case, the motion perceptibility was based on an exceedence of the average perception threshold. The reason for the difference in the number of occurrences of perceptible motion is related to the wind climate. In Sydney, the tower motion occurs during regular wind events that are part of the parent wind climate. In Brisbane the majority of perceptible tower motion events occur during thunderstorm events. As these are not part of the parent wind climate, this means that the extreme events are not related to the everyday events and occur as discrete events of relatively short duration. As a result, there are not the regularly occurring motion events that are perceived in the Sydney ATCT. It can be concluded that this is a major contributor to the reason that complaints were received at Sydney ATCT about perceptible tower motion, but similar complaints were not recorded at Brisbane ATCT.

Education, Exposure, and Expectation

The fact that the Sydney ATCT had been newly completed at the start of the field studies and access was provided partly on the basis of complaints was very valuable for this study. The previous control tower at Sydney Airport was a squat, masonry clad structure that would not have experienced any perceptible motion. As can be seen from Figure 1, the new ATCT has an unusual architectural and structural form with little apparent support beneath the cab. This combination led to a rare opportunity to educate the occupants about the accelerations. One initial concern was related to the structural reliability of the tower. This was allayed by the presence of the (supposedly knowledgeable) interviewer in the tower on windy days. In this way it was possible to reassure the occupants about the safety of the tower.

As part of the exit survey, the occupants were asked about their changing reactions to the tower motion. The results of this are shown in Table 2. It can be seen that the dissatisfaction reduced with increasing exposure. This implies a significant reduction in the "fear and alarm" component of occupant dissatisfaction with reassurance about structural safety.

Table 2 Questions and responses about the acceptability of the motion environment in Sydney ATCT from exit survey at end of study

QUESTION	RESPONSE			
	YES		NO	
	No. of responses		No. of responses	
When you first started work in the new Sydney Airport tower, did you consider the wind-induced motion environment to be acceptable?	19	50%	19	50%
Do you now find the wind-induced motion environment to be acceptable?	27	71%	11	29%

The perception thresholds from early-period and late-period interviews were also analysed by examining responses from late 1998 and from late 1999. This showed that the average perception threshold dropped slightly, confirming other work in the field of human vibration (e.g. Parker et al., 1978) showing lowered thresholds of perception in subjects regularly exposed to vibration. This finding seemed to be contradicted, however, by an increasing number of respondents reporting that the motion was "barely perceptible" rather than "clearly perceptible". The most likely reason for this is the fact that the controllers were being interviewed in the break room, without necessarily previously being aware of the presence of the interviewer, about their experience in the control cab in the previous 15 minutes. This implies that although the regular exposure made the controllers more sensitive to being able to feel the motion, they were actually noticing it less; another important finding in the assessment of habituation and supported by other studies in related areas (Woodroof and Griffin, 1987).

While Table 1 indicates that there was no data from the POCC about occupant complaint, there was some anecdotal evidence about reaction to the motion from informal conversation with the occupants. The occupants of the tower were all former mariners. As such, they were accustomed to working in a moving environment, even if this is not the type of environment that would normally be expected in a building. As the tower had been opened in the 1970s, it had been operating for over 20 years. The fact that the tower swayed perceptibly in the wind was well known and there was an element of long-term education about the structural reliability of the tower, just based on the longevity of the known issues and the fact that there was no structural damage to the tower. This type of education was enhanced in this case due to the small numbers of staff, and the low turnover whereby any new member of staff joining the working team and experiencing the motion for the first time could be reassured by more experienced occupants that the motion was normal and to be expected on windy days. Due to their nautical careers and experience, the motion did not appear to unduly annoy or disturb any of the occupants.

The expectation of motion is also important and, while it has been shown that complaints were lower in Brisbane ATCT where the peak events were caused by thunderstorms, part of the reason that such storms may not have caused fear and alarm may be the knowledge of the tower occupants of the approach of the storm. Thunderstorms are transient events with peak wind speeds that may last only a few minutes, and a rapid increase in wind speed at the onset of the storm. Clearly working in an air traffic control environment, the controllers are very aware of the approach of thunderstorms and their workload may be temporarily increased around the period during which this type of storm passes the airport. In other types of buildings, however, the occupants may not be aware of the approach of this type of storm and sudden onset of building motion may cause an increased level of fear and alarm as reported by Kijewkski et al. (2012) in a tall building in Chicago.

Psychological Factors

The results of the Sydney ATCT exit survey were subjected to a factor analysis, which is a standard method of establishing relationships in order to reduce a large number of questions, or variables, to a much smaller number of coherent, relatively independent, subsets (see Tabachnik & Fidell, 1987). From the thirty eight questions included in the exit survey, twenty three variables were identified, having removed the most obvious cases of similar and inter-dependent questions, on which to perform the factor analysis. The factor analysis then identified six major factors that were named to reflect their influence in motion perception and tolerance. Some of the key findings as related to the factors are summarised below.

Factor 1: Neuroticism.

This factor was related to irritation/annoyance and disturbance/fear. Other salient loadings on this factor were related to a high complaint rate and non-acceptance of the motion environment.

Factor 2: 'Static-ism'.

This factor showed positive loadings on each of the questions regarding frequency of acceptability of different perception and comfort measures, indicating a lack of acceptance of any perceptible wind-induced tower motion. This factor was, however, completely independent to Factor 1, neuroticism, which was the principal factor driving complaints. There was, though, a salient negative loading on acceptance of the current motion environment, indicating discontent. This is an important point in examining studies which are used to develop design criteria. An example of this is Hansen et al. (1973) who based their criteria on questions put to a building population on how many occurrences per year would cause them to object. On the basis of the factor independence discussed above, this type of questioning is not an appropriate technique for predicting potential complaint rates.

Factor 3: Sickness susceptibility.

This factor showed salient loadings on questions regarding physiological symptoms related to wind-induced tower motion. Again, this was an independent factor to neuroticism and also independent to non-acceptance of the motion environment. This is a surprising result as it would be assumed that there would be a strong correlation between motion sickness and dissatisfaction.

Factor 4: Insensitivity.

This indicated the occupants who were least sensitive to the motion.

Factor 5: Contentment.

This was related to the individuals who were satisfied with the motion environment in the tower.

Factor 6: Motion overestimation.

The two variables displaying salient loadings in this factor were size of motion and thermal comfort. This is an interesting link suggesting that those subjects who estimated that the amplitude of motion was very large also thought that their thermal comfort affected their motion perception. Perhaps this factor might also almost be considered a "hysteria" factor.

The key findings here were the lack of correlation between complaint and dissatisfaction and the occupants who believe that perceptible motion should not occur in buildings. This throws doubt on the basis of a number of common acceleration guidelines that were based on judgements from asking building occupants how often perceptible motion is acceptable. The findings of this study show that this will not give any indication of the subsequent complaint rate within a given population.

OTHER FACTORS TO BE CONSIDERED IN SETTING ACCELERATION TARGETS

In addition to the field experiences reported above, there are a number of other factors that need to be taken into account in selecting suitable acceleration criteria. Some of these are discussed in the following paragraphs.

Socio-Economic Factors

This is a rarely discussed subject partly, perhaps, because it strays into areas that may make engineers a little uncomfortable. The key question is whether it is acceptable for some types of building occupants to experience more motion than others. There is anecdotal evidence that larger perceptible building motions in residential apartments may be acceptable when other aspects of the housing are a significant improvement on tenants previous accommodations, or when the housing engenders a sense of community or wellbeing. One example of this was when some high-rise housing that replaced inner-city slums was being demolished in Glasgow around ten years ago. In an interview, one long-term tenant noted that "they did sway in the wind, but they were lovely houses" while noting that in their demolition "they took a lot of memories with them" (The Scotsman, 2002). Conversely, purchasers of very expensive accommodation (the most expensive of which is often located in the areas of a building that may be expected to experience the largest motions) may have a financial interest in finding building motion unacceptable.

Geographical Factors

Geographical factors also need to be accounted for in the selection of acceleration criteria, as this can affect the reaction of building occupants to perceptible motion. While there has been no work conducted to determine whether there are any differences between reactions to motion based on ethnicity, there are geographical factors that play into reactions based on expectation. A prime example of this is in earthquake prone regions. In these regions, the first reaction to perceived motion may be to leave the building as quickly as possible. While this may be an appropriate reaction during a seismic event, it is clearly undesirable if the cause of the motion is an extreme wind storm. If the perceptible motion is resulting from a wind event with plenty of warning, such as a typhoon, this reaction becomes less likely than if it occurs from a transient wind storm, as discussed above, with little warning of its approach.

Uncertainties in the Accuracy of Acceleration Prediction

The prediction of accelerations during design is not completely accurate with differences from field performance of the completed building arising from a number of sources.

The first, and potentially most significant, area where there is uncertainty is in the definition of the wind climate at the site. Wind climate data is often far from perfect and the wind engineer has to produce a statistical fit to either the wind climate data and/or the predicted responses. With a tall slender building undergoing cross-wind excitation a 10% difference in wind speed can result in a change in accelerations of 30% or more. This potential error is increased in regions that experience a mixed wind climate with multiple storm types affecting the extreme wind speeds. The length and quality of the available meteorological data set also sets boundaries on the accuracy of the prediction. The site wind speed is also very dependent on the upwind terrain. While there are well proven analytical techniques that take into account the effects of ground roughness to allow wind speeds measured at a meteorological station to be transferred to the site, these techniques lose reliability when this is coupled with significant topography.

Most acceleration predictions are made for conditions of surroundings extant at the time of design. In dense city environments, the surrounding buildings will change with time. In rare cases, interference from isolated new buildings may increase the accelerations but, more generally, as surroundings become denser and taller the building responses may be expected to decrease. This is of less significance for building accelerations than for building loads, as issues with serviceability, such as occupant complaint, are more likely to surface in the first few years following initial occupation.

The predicted dynamic characteristics of tall buildings are often significantly different from those measured in the field on completed buildings. This difference is likely to reduce with time as building dynamics models become more accurate, but at present it is not uncommon to find differences of 30% or more between predicted and measured natural frequencies at low amplitude levels. In general, the design models tend to underestimate the field natural frequencies, which normally means that higher accelerations will be predicted during the design process than will be experienced in the field. Another key factor that affects the predicted accelerations is the prediction of inherent structural damping. This is an assumption that is generally made by the structural engineer, and about which there is little reliable field data. Engineers often select damping ratios purely based on their past practice and depending on their choice this can have a very large effect on the predicted accelerations.

APPROACHES TO REDUCTION OF UNDESIRABLY LARGE ACCELERATIONS

There are a number of methods that may be applied to reduce serviceability accelerations and these each have plusses and minuses associated with them.

Supplementary Damping Systems

One common approach in buildings that have been assessed during design to exhibit excessively large motions is the incorporation of supplementary damping systems. If these damping systems are being incorporated only to control serviceability accelerations then they may take the form of one or more discrete devices such as tuned mass dampers, tuned liquid dampers, or liquid column vibration absorbers. If, however, the dampers are also intended to reduce design loads it is more common to use distributed systems that incorporate a degree of redundancy. While damping designers generally promote the performance in terms of the reduction in acceleration at a given return period (most often the one associated with the acceleration design guideline being used), the real benefit of supplementary damping is in reducing the frequency with which perceptible acceleration occurs. One downside to many damping systems is the space cost of installing large enough dampers to significantly change the building response.

Aerodynamic Modification

The response of some tall buildings can be significantly altered by modifying the aerodynamic form of the building. In some cases this can be conducted by rotating the building so that a more favourable geometry is presented to the key wind directions. More commonly, this is achieved by modifying the shape of the building. Care needs to be taken in the application of this approach as depending on the design constraints and the wind climate this can have a counterproductive effect on either the accelerations and/or the loads when shaping is done in such a way as to maintain useable floor areas within a limited site (Denoon et al., 2012). Generally, though, this can be a very effective approach given an amenable architect.

Modification of Dynamic Characteristics

The responses of a tall building to wind excitation are dependent on the dynamic characteristics of the building and for most tall buildings the accelerations can be reduced by increasing the natural frequency of vibration of the critical modes. This often has only a small return, with the exception of modifications to stiffen a building in torsion, as with increasing natural frequency comes a reduction in the perception threshold. The increase in stiffness required to provide a large enough change in natural frequency to significantly change the acceleration may also come with a significant economic cost and in some buildings achievable stiffness increases may not result in significant changes to acceleration response (Huang et al., 2011).

PRACTICAL DESIGN CONSIDERATIONS

Rather than a simple “one size fits all” approach to determining acceptable levels of acceleration in a tall building, consideration needs to be given to a number of factors to ensure that the building is designed as efficiently as possible to meet a building-specific target performance that requires neither over-design nor results in occupant dissatisfaction following occupation. This section of the paper outlines a practical approach to ensuring this will happen.

Local Design Requirements

As has been noted there are some places where local design codes include prescriptive requirements for maximum allowable accelerations. If this is the case, and the requirements are judged to be conservative, then the building must be designed to meet these. Depending on the level of conservatism, it may be decided to make some other aggressive design assumptions in the estimation of building accelerations. The following sections can be used to determine whether the local code requirements are conservative for the building being designed.

Local Wind Climate and Building Type

The local wind climate should be assessed with respect to the building type and whether the building will be occupied during extreme wind events. For super-tall buildings, it may be appropriate to exclude thunderstorm events from the analyses as, having their peak wind speeds at a low elevation, they are unlikely to generate a significant resonant response in super-tall buildings. This is not the case for shorter buildings. In hurricane and typhoon prone regions, commercial buildings are likely to be evacuated during major storms and a higher acceleration may be considered, based primarily on safety and other serviceability limits, for this type of building. Note that this is not a distinction between office and residential buildings, but a distinction between occupied and evacuated buildings. The relationship between the extreme wind events and the everyday parent wind climate needs to be assessed in determining the relationship between the more extreme events causing fear and alarm, and the regularly occurring events that may cause annoyance as a result of regularly perceptible motion.

Expectation, Education, and Geographical Factors

In cities such as Hong Kong where there is a very high density of high-rise housing, there is a wider public knowledge of wind-induced motion of tall buildings than in locations where there are few tall buildings. As such, fear and alarm may be lower among a population educated to expect perceptible motion during identifiable extreme wind events. On the opposite end of the scale, unanticipated wind-induced motions in a seismic region may be expected to cause widespread fear and alarm at much lower amplitudes. With small population groups, such as air traffic controllers, it may be possible to educate them about wind-induced motion and mitigate fear and alarm in that manner.

Selection and Adaptation of a Baseline Guideline

There are a number of published guidelines and criteria as described earlier in the paper. Assuming that the designer is not statutorily bound by prescribed criteria, then the most appropriate guideline should be selected as a basis for assessment. It is clear that there is frequency dependence in occupant perception and reaction to motion. It is also the case that choosing a shorter return period for assessment will provide a better reflection of commonly occurring acceleration events than a longer return period. It has been shown that simply asking the client team about probabilistic measures of the frequency of occurrence of motion perception for different proportions of building populations is not likely to elicit responses that will be linked to actual complaint in buildings. It would also be desirable to choose a guideline that has a long track record of successful use. For this reason, the authors suggest the use of the office building curve of ISO 10137:2007 as a good basic guideline. This is frequency dependent, has a one year return period, and is based on the field experiences of a guideline that has been in use for over a quarter of a century. It also has the advantage in the eyes of designers, clients, and review teams of being a validated, published, and generally accepted international standard.

When a baseline guideline has been selected it is up to the design team to make recommendations to the client team about whether to relax the guideline or, more commonly, modify it to be more stringent. The factors discussed above are the items that should be brought into a basis of design recommendation to, or discussion with, the client team. The key is that the client team must take some responsibility for selecting an appropriate level of performance for the building under design based on the team’s understanding of its goals for the building and its understanding of the likely responses of the occupants to perceptible motion.

Assessment of Uncertainties in Prediction

While the assessment of uncertainties in the accuracy of prediction of wind-induced building motion may not affect the selection of a criterion, it does affect the interpretation of predicted accelerations in relation to chosen criteria. Accelerations are a serviceability issue, and it is thus possible to make more aggressive assumptions or be more flexible in the interpretation of results than is the case with life safety issues such as ultimate limit state wind loads.

CONCLUSIONS

This paper has reviewed current design guidelines for wind-induced motion of tall buildings and examined the factors that affect occupant tolerance of motion, and how to assess their reactions. A practical approach to selecting suitable acceleration guidelines for specific buildings has been promulgated, this approach taking into account numerous factors not reflected explicitly in current guidelines.

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