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MULTI-WAVE, NON-STATIONARY, PARAMETRIC LOAD MODEL FOR SEISMIC HAZARD ASSESSMENT AND PREDICTION

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SUMMARY

Assuming seismic ground acceleration to be a 3D stochastic non-stationary process, consisting of several transient and overlaying wave fields with distinctive characteristics und potential hazard, a parametric, predictive load model at sites of interest is proposed, based on the evolutionary (power) spectrum of the reference component defined by time-dependent stochastic principal axes and concentrating on separate wave fields and site specific resonance. The model turns out to satisfy conditions of conservative aseismic design and is considered to be a substantial improvement of currently applied load models in both practical application and physical transparency, with a prospect to lower costs for earthquake resistant building.

INTRODUCTION

Analysis and prediction of seismic load due to strong earthquakes is becoming more and more important, as seismic hazard increases rapidly with growing urban infrastructure in earthquake prone areas. Major economic centers of both western and developing countries are threatened by damages from strong earthquakes. As both theoretical analyses and structural performance in recent earthquakes show, current stochastic models for load prediction, assuming ground acceleration to be a kind of stationary process, do not meet the requirements of modern aseismic design. Usually, this lapsus is dealt with by generous, i.e. expensive, security factors, which cover a very broad frequency domain, complemented by local amplification classification.

Nevertheless, strong ground motion at a site of interest is more adequately represented by stochastic non-stationary models [1]. Asides its both long-term and local stochastic characteristics, there is a real, deterministic physical process in the background, whose characteristics express in every record of ground acceleration but are not reflected in current seismic load models. While the rupture process itself cannot be neglected in the near field, but is rarely predictable in prospect, local modulation and especially amplification of the radiated energy seems to be far more important for most sites of interest [2,3] and can be assessed with more certainty at reasonable costs.

For aseismic design, physical transparency of the load model is necessary on the one hand, in order to cover most important features of the physical process with potential to structural damage, and simplicity is

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desirable on the other hand, in order to promote practical application amongst engineers and reasonably limit costs for load prediction itself.

We propose a parametric stochastic non-stationary model suitable for both analysis and prediction of seismic load, enabling a deeper understanding of the nature of non-stationarity in seismic ground acceleration with respect to structural damage and a more adequate and less expensive, but still sheer conservative, aseismic design.

NON-STATIONARY CHARACTERISTICS OF DESTRUCTIVE GROUND MOTION

Seismic strong ground motion is characterized by several non-stationary features. From an aseismic design point of view, we concentrate on most important characteristics of destructive seismic ground acceleration at a site of interest, which are poorly covered by current seismic load models.

First, it is obvious from the wave equation and every observation, that there are several wave fields of different seismic wave types, which cause specific reactions in a structure's life critical parts and inflict cumulative damage to its overall stability. While current methods concentrate on transverse or S-waves, there are other wave types, first and foremost direct longitudinal or P-waves, and furthermore guided and surface waves, which are in certain, even frequent cases, important for structural damage.

Second, these wave fields are transient, which means that long stationary phases are rare. While many of them overlay at a site, there are clear phases of dominance of particular wave types, which are dangerous as they may ignite destructive structural resonance These phases are caused by different wave velocity of direct waves, and by the fact that indirect waves are generated by direct waves later, near the site, at certain discontinuities of (sub)surface topography. While having smaller amplitudes, they may have far longer duration than the direct waves. Cumulative energy of those phases is relevant for damage rather than singular peak values.

Third, the process of structural damage is a resonance phenomenon. The frequency distribution of the seismic energy at the site is therefore of utmost importance. For most sites of interest, the subsurface is layered soil, acting as a resonant system with fundamental modes determined by layer thickness and wave velocity. If amplification is really a function of local characteristics, these fundamental modes should dominate the spectrum at the site and should be relatively invariant with respect to source characteristics and location.

Fourth, earthquakes are rare events with many uncertain influence factors. Therefore seismic ground acceleration is best modeled by a stochastic process, but a particular earthquake can be merely considered a realization of that process. In order to capture average dominant characteristics of the process at the site, which are in the focus of interest rather than particular effects of a singular realization, general assumption of ergodicity is required and parameters of the model must be determined by statistical analysis of adequate statistical entities.

The differences of the wave fields in directional, velocity, frequency, energetic and duration characteristics are quite strong [4], which suggests to model these wave fields as separate stochastic entities, expressed as wave dominance phases, which can be clearly seen from analysis of the course of time-dependent stochastic principal axes [5,6].

Last, but not least, seismic acceleration really is a 3D process, and any 1D approximation should preserve major characteristics relevant to structural damage, which is usually not the case. In contrast to usual assumptions in aseismic design regulations, recorded components are generally highly correlated, when focus is turned to small time windows [7].

PARAMETRIC, MULTI-WAVE, EVOLUTIONARY SEISMIC LOAD MODEL

In order to describe as well as to predict the seismic load process due to possible rupture scenarios at a specific site with certain soil conditions and (sub)surface topography, a parametric model is required, which covers the abovementioned non-stationary and physical characteristics and delivers unique values for this site. The parameters must be chosen in a manner which transparently reflects significant features of seismology, structural and soil dynamics, allowing scaling the model accordingly. They must be easy to determine by objective criteria from measurements and reasonable engineering assumptions.

The proposed model is based on the evolutionary spectrum [8,1,9] of the reference component of seismic acceleration defined by time-dependent stochastic principal axes [10], covering time- and frequency dependence of seismic load as well as the usually neglected, but nevertheless strong component correlation. While it is also possible to use the PHA component instead, the reference component is the preferred choice, because it includes all dominant waves of the 3D process, is uniquely defined and easy to determine for every recording site. The proposed load model is a superposition of the sub-processes corresponding to separate wave types and called Empirical Evolutionary Spectrum

$$EES(f,t) = \Sigma_{w = P,S,C\backslash G}\, EES_w(f, t) \qquad (1)$$

Corresponding to a one-phase rupture, three wave phases W = P, S and C\G are modeled. Major direct wave types P and S, while originating from the same source, are usually at least partly separated in seismic ground acceleration at the site, due to their differences, amongst others, in wave velocity. Their successive wave fields hence establish different stochastic entities, which express in accelerograms as phases characterized by the dominance of the particular wave type, and are therefore modeled separately. Converted, reflected, guided and surface waves are generated later and, in the last case, do not have a linear, but an elliptical mode of particle motion. These indirect waves establish one or more separate stochastic processes as well. In order to preserve simplicity and because of lack of good separators for these partly occasional wave fields with very short phases of dominance, they are modeled together in a single wave phase, i.e., as a common stochastic sub-process named C\G.
The evolutionary spectrum of each of the three wave phases is modeled by the product of parametric shape functions $SP_w(f, \vec{p})$ and $AMF_w(t, \vec{q})$ for (stationary) power spectrum and time-dependent amplitude modulation, resp.

$$EES_w(f,t) = SP_w(f, \vec{p}) \cdot AMF_w(t, \vec{q}), \qquad (2)$$

The spectral shape function is supposed to replicate the resonance behavior of the local layer package, which incorporates essential site effects – soil resonance and local damping. We base our choice on the well known Kanai-Tajimi spectrum

$$KTS(f) = S_0 \cdot \frac{1+4\zeta_g^2\phi^2}{\left(1-\phi^2\right)^2+4\zeta_g\phi^2}, \ \phi = f/f_g, \qquad (3)$$

which describes the fundamental mode of spectral amplification of an incident wave with white noise spectrum by a single soil layer [11]. KTS is controlled by three parameters ζ_g, f_g and S_0, which are Lehr's damping measure, un-damped resonance frequency and average spectral amplitude of the incident wavefield, respectively.

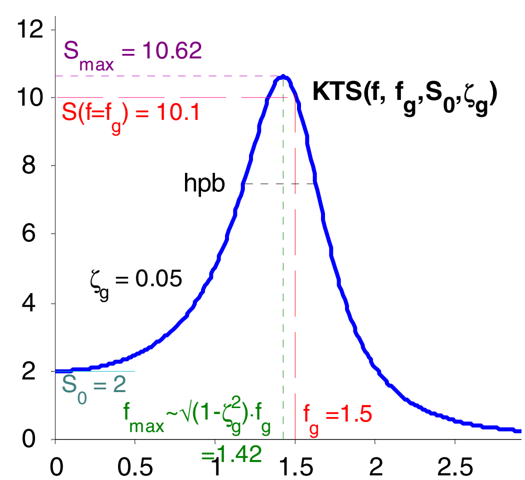

Fig. 1 shape characteristics and distinctive parameters of the Kanai-Tajimi-Spectrum

In order to model spectral amplification of several layers and/or modes of resonance, we extend (3) by superposing multiple KTS according to the number n of observed or predicted resonances to Multi-KTS

$$MKTS(f) = \Sigma_{i=1,\dots,n}\, KTS(f, S_0^i, f_g^i, \zeta_g^i) \tag{4}$$

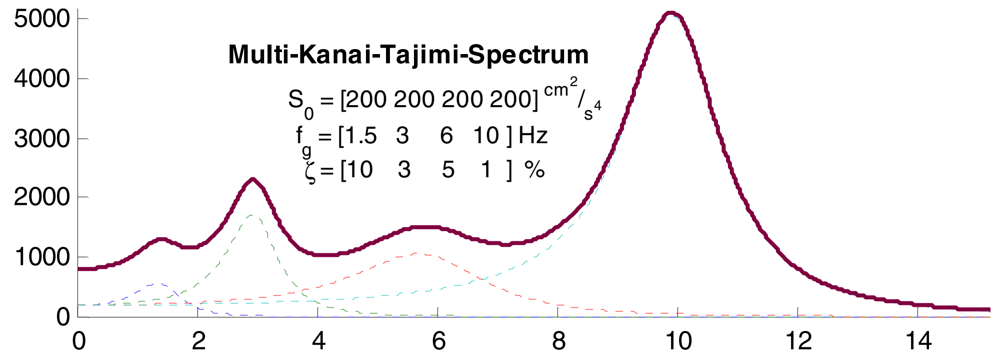

Fig. 2 Example of a Multi-KTS with four modes of resonance and distinct damping values, caused by an incident wave field of total acc. evolutionary spectral amplitude ΣS_0 =800 cm^2/s^4.

It is reasonable to assume that the number of resonances as well as the f_g^i and ζ_g^i are locally bound parameters, while S_0 account for macroseismic effects and are expected to show some kind of source-to-site-distance plus magnitude as well as azimuthal dependency. Additionally, as empirical analyses have shown, there are typical spectral domains for different wave types, from higher frequencies for P-waves to possibly very low fundamental modes of surface waves.

The shape function for the amplitude modulation shall have the functionality of an envelope in the model and account for strong motion duration and transient character (rise and decay) of the seismic wave fields in the time domain. These are determined by rupture type and duration, source-to-site distance and local effects. For the purposes of the aspired load model, a proposition of Sugito & Kameda [12] has been transformed to yield more significant parameters, κ, τ, and c which describe peak amplitude, the time of its occurrence and shape, respectively.

$$AMF_w(t,\tau,\kappa,c) = c \cdot t^{\frac{ln\frac{\kappa}{c}}{ln\tau - 1}} \cdot e^{-\frac{t}{\tau}\cdot\frac{ln\frac{\kappa}{c}}{ln\tau-1}} \tag{5}$$

Transformation (5) also allows to normalize the function to κ=1 and therefore preserve the maximum spectral amplitude when multiplying AMF_W with the corresponding spectral shape function SP_W. Peak occurrence τ is supposed to be clearly linked to wave types, because of different wave velocities and genesis. Additionally, it is assumed to have a naturally dependence on distance, because wave phases are prolonged with traveling time. Similarly, the shape of the peaks is expected to flatten slightly with distance and more pronounced with wave types in the same order as τ does. In order to preserve the necessary convex shape of the function, parameters must meet the condition

$$c >(<) \kappa \quad \wedge \quad \tau <(>) e = 2.7183...$$

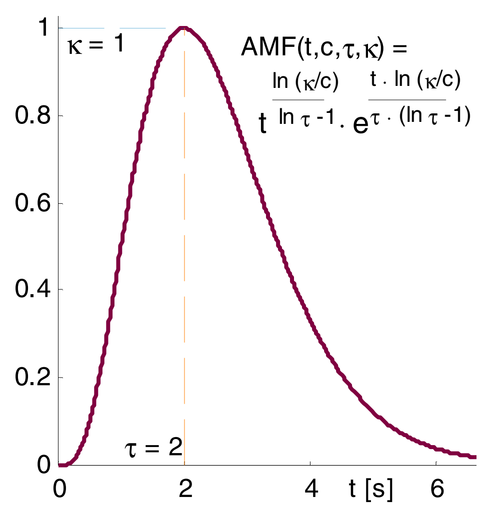

Fig. 3 Definition and meaning of the parameters of amplitude modulation function (5)

A PROCEDURE TO ESTIMATE THE PREDICTIVE LOAD MODEL

The load model EES consists of wave phases and corresponding parametric shape functions, which serve as the backbone covering the physical process. In order to qualify the model for predictive purposes, it must be complemented by empirical scaling laws and rules for the correct choice of the parameters with respect to parameters of macro-seismic, soil and structural dynamics, which account for statistic properties of the seismic load process and local site conditions. In order to derive these empirical relations, a statistically significant sample of the stochastic process must be analysed. Assuming ergodicity, a procedure to estimate model parameters, consisting of several steps, is proposed, based on classified datasets of well recorded strong earthquakes, which are realizations of the stochastic process at particular sites.

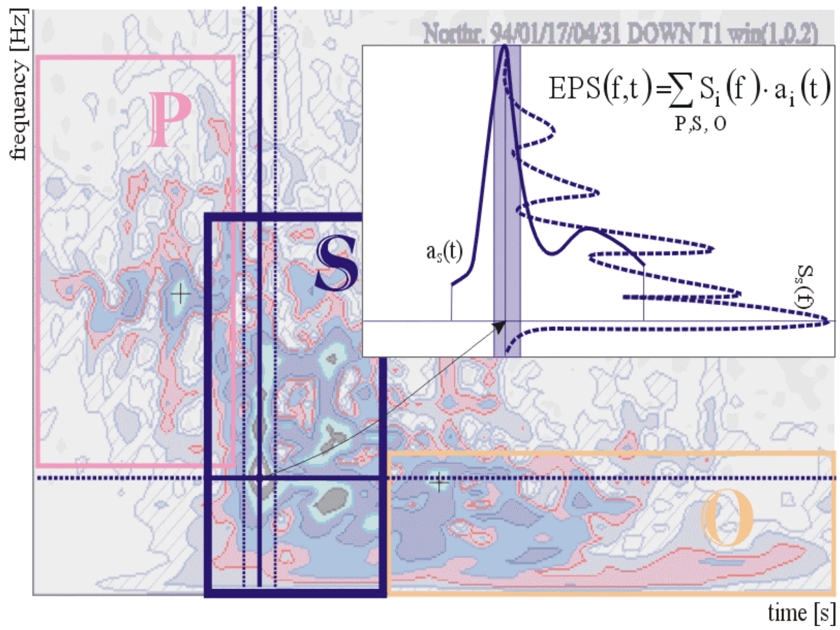

Fig. 4 Approximating load of evolutionary sub-processes corresponding to distinct wave fields P, S (pronounced) and C\G or O by a product of slices representing spectral and temporal modulation, crossing at the maximum peak of the wave phases, used for parametric shape functions fitting

First, the recorded components should be transformed onto time dependent stochastic principal axes in order to determine the reference component [10], which contains the dominant parts of all wave fields in the original accelerogram and therefore is a more appropriate 1D approximation of the 3D process than the usually chosen PHA component. An inherent quality of this component is that it is superior in energy to all original components in any time interval. A very important byproduct of that procedure is the time dependent stochastic principal axis itself, which describes the principal direction of the axis of particle acceleration of the corresponding wave field in the reference component. While the PHA component may also be used, strict conservativity as well as independence of definition are not granted in this case and additional methods for the determination of wave phases are necessary.

Second, the evolutionary spectrum of the reference component is estimated – there is no way to describe the evolutionary spectrum analytically. This can be done by a multi-filter method proposed by Kameda [13] and improved by Scherer [14] or other well-known methods.

Third, dominance phases of wave fields must be identified and the corresponding sub-processes in the evolutionary spectrum of the entire reference component must be separated. We use the course of the time-dependent stochastic principal axis, represented by specially chosen spherical coordinates, to identify the changes of dominance of the wave fields of interest [6], which are limited to three wave phases P,S and C\G as described above.

In the fourth step, the load process of every dominant wave field is approximated. In a straightforward approach this is done by the product $XES_W = sp_W \cdot amf_W$ of two slices sp_W and amf_W extracted at the maximum peak of each wave phase along the frequency and time axis, respectively (see Fig. 4). Singularity and uncertainty of peak values is considered by averaging the spectral slice.

In the fifth step, parameters of the load model at the specific site and for the specific event are determined by least-squares-fitting the shape functions of choice to the extracted slices.

These steps, carried out for data of one or more strong earthquakes recorded at a representative group of sites, yield a set of descriptive, parametric load models which serve as the statistical basis for scaling and design relations of the parameters of the predictive model to seismological parameters of the event(s), as well as to topographic and soil classification of the site. Together with the time-dependent stochastic principal axis, which carries information about the directional characteristics of the modelled wave fields, these models can serve as a tool to analyse and classify these records with respect to non-stationary characteristics.

Example

In this contribution, we concentrate on results indicating the significance of the parameters and shape functions. Nevertheless, the estimation procedure is illustrated, as an example, by the well known CSMIP record of the 1994 Northridge earthquake at Tarzana, Cedar Hill Nursery (see Fig. 5 and Fig. 6).

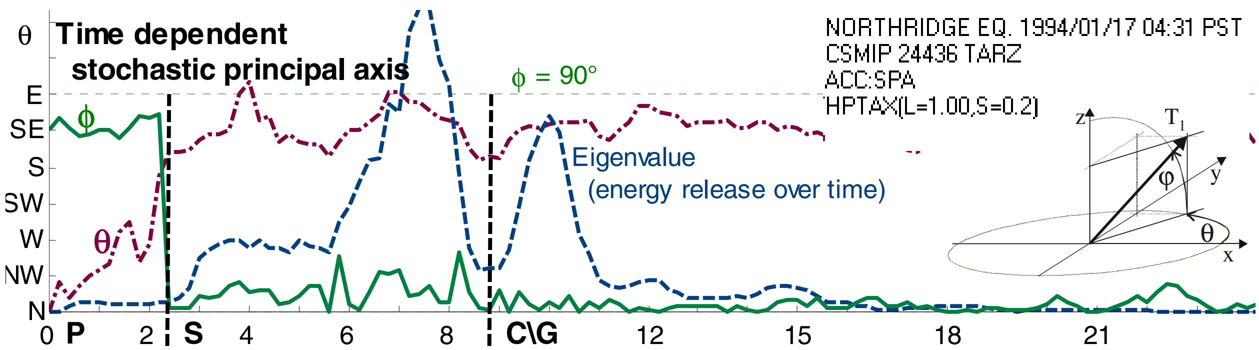

Fig. 5 **Course of the time-dependent stochastic principal axis of the Northridge '94 record at Tarzana in certain spherical coordinates (s,φ,θ) , whose definition is illustrated to the right in terms of the regular, cartesian coordinate system (see [6]), with 80% overlapping moving time windows of 1sec length.**

Located 20km south of the epicenter atop a small foothill of the Santa Monica Mountains, the record shows clear phases of P and S wave dominance, indicated by the plateau of high values of the vertical angle φ at 0-2.2s, then abruptly flooded and concealed by the field of direct S waves, indicated by constant low values of φ. Polarization of S waves is indicated by the horizontal angle θ, generally coincident with the South-East oriented transverse axis of the hill as well as rupture strike. Strong topographic resonance of the hill was incited by the direct S waves, which massively exceeded PGA of the direct S waves (factor 6 in terms of the principal axis) and resulted in the famous 1g+ PGA values which made the site subject to several in-depth investigations, e.g. [14]. The length of the S phase was chosen equal to the rupture length. The second peak of the hill resonance was assigned to the phase of converted waves and may be due to S waves of a second rupture segment [21,22], which was located further north and therefore arrived later, but was concealed by the first resonance of the hill. Indeed, the resonance of the hill had characteristics of a Rayleigh wave, as both vertical and horizontal components had very high excitations within all wave phases.

The course of time-dependent stochastic principal axes is a very sensitive indicator for directional characteristics of seismic waves. In general, phases of direct P and S waves express very clearly in accelerograms recorded at free field sites, as already stated in [6]. Significant markers for the change of the wave type have been found to be stable with respect to the windowing parameters. Certain typical features can be identified for dam records, e.g. Pacoima Dam for the Northridge Earthquake.
The three wave phase model has been verified and coincidence with recorded data was obvious for the middle and far field. In the near field, if there are separated rupture phases, as indicated by seismological rupture models [22, 21] as well as by the course of the stochastic principal axis for several sites of both Northridge 94 and Landers 92 earthquakes, there may be need to extend the estimated, descriptive model to multiple direct wave phases in order to sharpen the accuracy of the estimated parameters. The predicttive model may nevertheless remain restricted to three wave phases in general, less sensitive cases where normal design regulations apply.
Approximation of the share of seismic load most relevant to structural damage by extracted functions sp_W and amf_W at the maximum local peak of the evolutionary spectrum of each wave phase has been proved to be a valid approach. The dominant peak is well described by the product of these functions, while less significant peaks and noise are neglected. The approximation yields a stable and almost constant loss of energy due to the neglected parts, which can be modeled by a constant correction factor, shifting lost energy to frequencies more relevant to damage – which is a selective conservative approach.

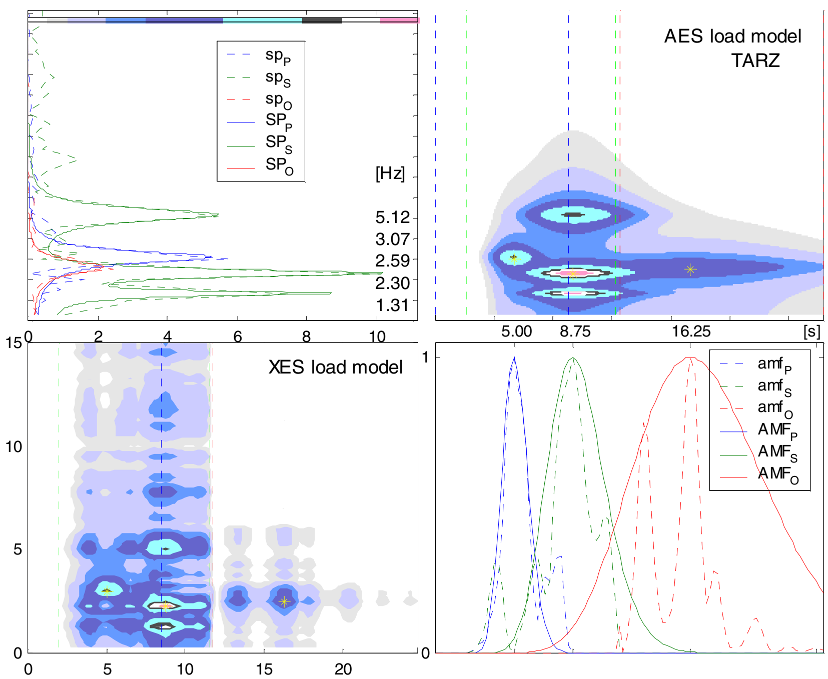

Fig. 6 Comparison of the estimated parametric model (upper right, contours with P,S (overlapping) and C\G wave phases indicated by dotted lines, peaks by stars) – nonlinear-least-squares-fitted shape functions (solid lines, AMF_* and SP_*) with the model corresponding to the approximation step (bottom left, as well) – extracted slices (dotted lines, amf_* and sp_*) for the N94 Tarzana record.

The parametric shape functions SP_W and AMF_W chosen for spectral and amplitude modulation approximate the shape of the extracted functions sp_W and amf_W in a generally good fashion. Especially the Multi-Kanai-Tajimi-spectrum is a very good model for evolutionary spectral modulation, proving the adequacy of the assumption of layered soil packages for site grounds as well. Both resonance frequencies and spectral amplitudes are in very good agreement and energy, in terms of the integral of the functions, is being conserved, with neglectible average errors of some 5%. For the AMF (5), there was generally good agreement of shape for the P-Phase, but less agreement with partly considerable gain in energy for the S- and even more for the C\G-Phase. While the functionality of a conservative envelope is granted, the energetic surplus is not similar to the intended loss of energy in the approximation step and must be decreased. Several reasons for the problems with that particular AMF have been identified, but its correction is not simply straightforward and left for further research.

SIGNIFICANCE OF LOAD MODEL PARAMETERS AND ASSUMPTIONS

The CSMIP dataset of the 1994 M6.5 Northridge earthquake (N94) has been appraised in conjunction with those of the 1987 M6.1 Whittier Narrows (W87) and the 1992 M7.2 Landers (L92)earthquakes, to estimate parameters and corresponding scaling laws and domains of validity of the parametric seismic load model (1) in conjunction with (2),(4) and (5), based on site classification according to distance, regional proximity (azimuth) and local geology [16,17] as well as additional site information [18], totaling in some 150 sites in the L.A. region.

The most impressive confirmative result was stability of the fundamental modes of resonance at sites which recorded two or all three of these earthquakes, being at quite different distance and azimuth to the faulting zones. Certain stability of resonance frequencies in the evolutionary spectrum was expected, as verified for Fourier amplitude spectra of Northridge records by Trifunac [19], who has recently confirmed his results with data from former Yugoslavia [20] and San Fernando 1971 [SDEE 1 2004].
In the dataset of congruent recording sites of the three abovementioned strong earthquakes in southern California, there is indeed very high re-occurrence of the frequency bands where peaks in the evolutionary spectra of the reference component where identified. For our analysis, we defined two degrees of strong and very strong conformity by occurrence of dominant peaks in the estimated MKTS (4) of two records in a range of 0.5Hz and 0.25Hz from each other, respectively. These values match twice and once the resolution of the evolutionary spectrum estimate in the frequency domain, i.e., the best possible level of accuracy. Up to five dominant peaks were compared for each wave phase.
There were 18 congruent sites of N94 and L92 and 26 of N94 and W87 at all (see Fig. 7). Very strong conformity (range ≤ 0.25Hz) occurred at between 20% and almost 50% of the sites in the direct wave fields P and S, while in the C\G wave phase, there were even two thirds and more of the sites with very strong conformity. Adding sites with only strong conformity, i.e., most adjacent dominant frequencies were in the range of up to 0.5Hz from each other, the total share of sites with re-occurring dominant frequencies was between more than one half for the P phase, more than three quarters for the S wave phase and even almost all for the C\G wave phase. More than 50% of the re-occurring frequencies were amongst the first three dominant frequencies for all wave phases, and up to a quarter of the congruent sites had more than one re-occurring resonance during the S and C\G wave phases.

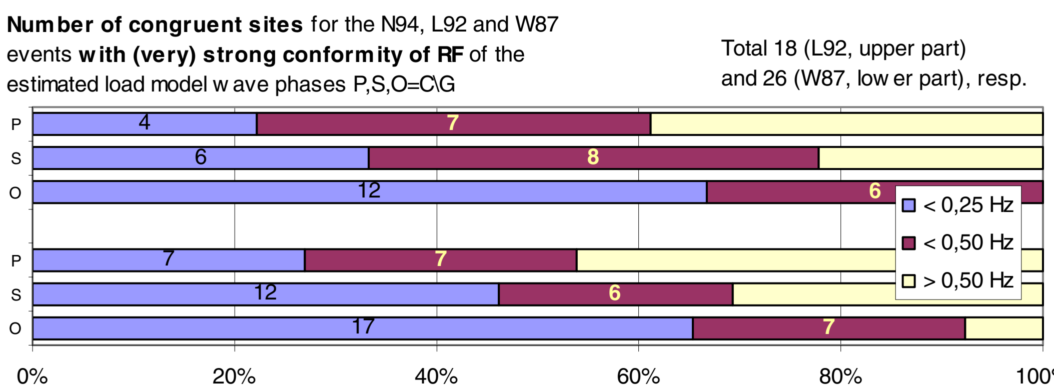

Fig. 7 shares of very strong and strong conformity of dominant frequencies amongst congruent sites of N94-L92 (upper) and N94-W87 (lower part), separately for the wave phases of the load model

While the high re-occurrence of resonant frequencies in the C\G phase may partly be due to the usually quite narrow spectral domain of typical fundamental modes for surface and other indirect waves, these results are a very strong indication for the permanent nature and load defining character of the local resonance system and hence for the relevance and workability of that system in the context of aseismic design. This underlines the necessity to apply non-stationary spectral analysis instead of the usual blurring of this physically significant effect by methods which imply far-reaching stationarity assumptions.
A reasonable explanation for the existence of sites where no conformity in the abovementioned sense was observed is that due to more complex regional and local topography and non-linear attenuation with distance, different resonance regimes may have been activated. The extent of this phenomenon is to be further empirically investigated.

Another assumption that, for stratified sub-surface with nearly linear-elastic material, resonance frequencies are connected with wave types in a decreasing way from direct P and S waves to indirect waves, was confirmed by the dataset. At relative standard deviations of 70%, the median values of the strongest resonance frequency of the P, S and C\G wave phases were 3.6Hz, 2.3Hz and 1.8 Hz, respectively. This is another reason to consider major different wave fields separately in efforts to predict their seismic load.
A very slight decay of the strongest resonance frequencies was observed for the direct wave fields P and S, which can be attributed to the fact that high frequencies in the bedrock spectrum are damped stronger and that duration of the wave fields is increasing with distance, hence leaving relatively more energy and longer time for incitation at low frequencies in the far field. C\G phase strongest resonance frequencies had no apparent dependency on distance. This confirms that Coda and guided waves are converted direct waves, whose generation afar of the rupture depends on regional and local (sub)surface topography and concentrates on lower frequencies.

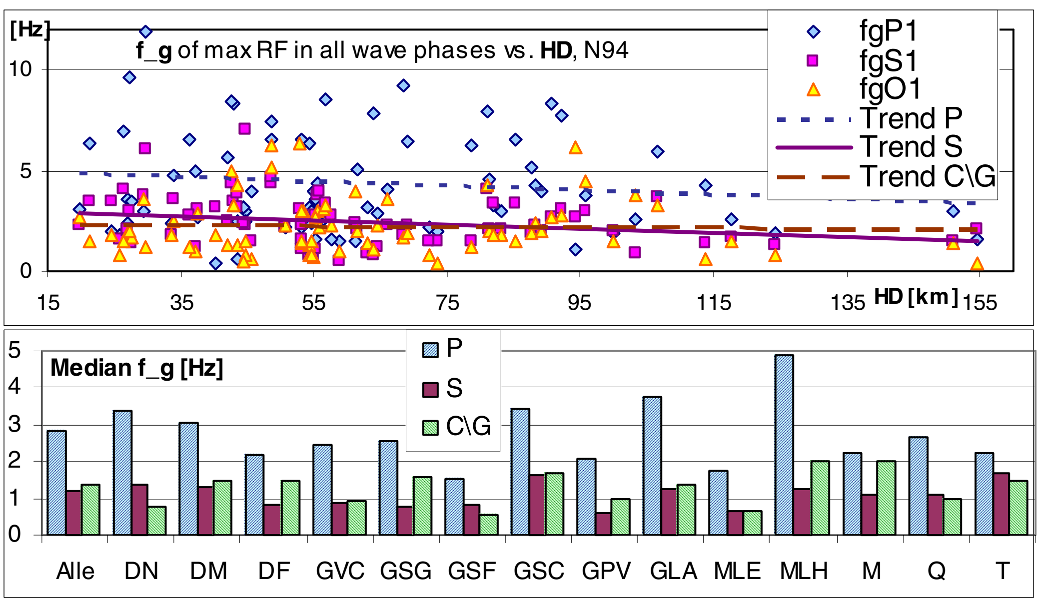

Fig. 8 Distribution of the strongest resonance frequency in the P,S and O=C\G wave phases of the estimated load model versus hypocentral distance (upper) und for site classes (lower part), CDMG, N94. Site classes are with respect to distance (D* for near, middle and far field), regional adjacency, i.e., close range of azimuth (G*) and soil classes according to Park 1998 [16].

A surprising result was that there was apparently no clear dependency of the resonance frequencies to soil classes neither by Park & Elrick [16] nor Tinsley & Fumal [17] and even a broad regional variation within these classes, especially in the P wave phase. As an example, average resonance at sites around Lake Hughes classified as mesozoic according to [16] was almost 5Hz, but only 1.8Hz for sites of the same class in the Leona Valley array, just 20km away. While soil resonance is solidly linked with elastic soil properties, especially wave velocity, this means that these general soil classes are not suitable to adequately describe the local soil resonance system. These classes can only reflect a general, macro-seismic regime of amplification, which is not connected to local resonance.

Amplification corresponding to resonance frequencies, besides subsurface topography the most frequent contribution to site effects, is expressed by the damping parameter ζ_g. A domain of realistic values for this genuine locally bound parameter is from 1‰ (hard rock) to 10% (loamy, highly saturated sediments). Estimated parameters ζ_g for the strongest resonance peak in the N94 dataset were almost completely in this range, while values near the boundaries were rare, a realistic result.

Further statistical analysis revealed a broad distribution of ζ_g independent from distance similar to the resonance frequency. Standard deviation was high for all site classes, especially also between regional groups of adjacent sites with the same soil classification. Notable differences in median damping were found for the different wave phases and with respect to general soil classes. While S wave resonances seemed to be damped generally stronger for lower wave velocities (or decreasing stiffness), P wave resonances had similar damping for quaternary and mesozoic sites, characterized by low (300m/s) and high (600m/s) average wave velocity, and significantly higher damping at tertiary sites (450m/s).

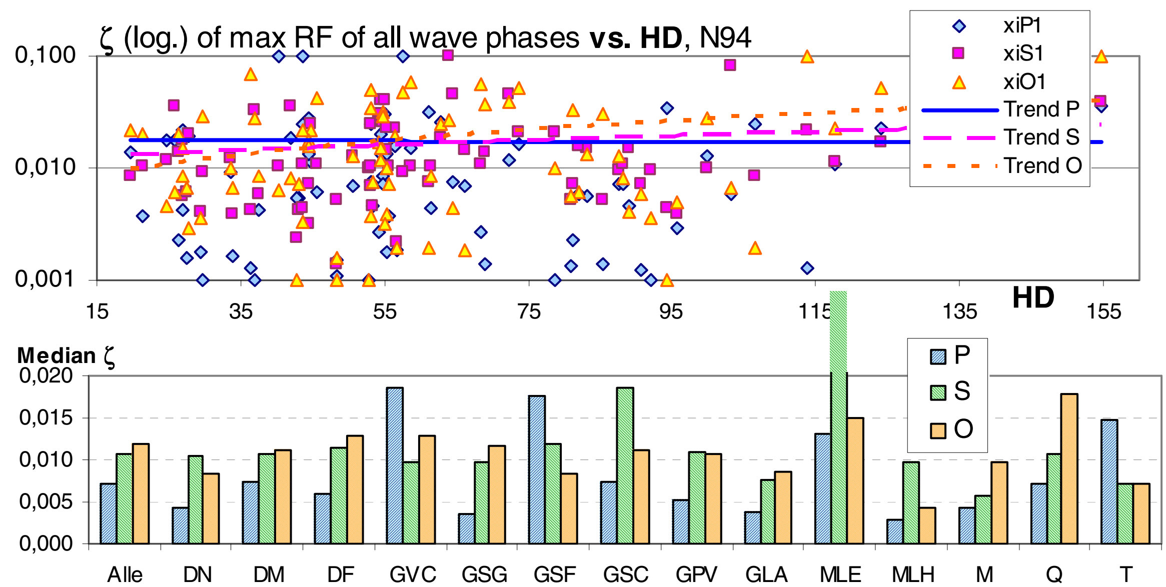

Fig. 9 Distribution vs. hypocentral distance (upper part) and median analysis for damping parameter ζ of the strongest resonance frequency in the estimated models, no significant trends.

For the phase of indirect waves, quaternary sites had the strongest values of ζ_g. As a rule, ζ_g was higher in the S phase than in the P and in the C\G wave phase as well. This is what is expected because, while origin, propagation path and local soil stiffness are the same for P and S waves, P waves have considerable higher frequencies, and Lehr's damping measure ζ_g is linked to resonance frequency f_g, on the one hand, and there is no additional radiation damping for indirect waves, which are, for the most part, guided waves. Because of its massive influence on spectral amplitude and due to its strong local variability, for a strictly conservative predictive load model, the parameter ζ_g must be set up as a statistical lower bound (which overestimates amplification), which can be increased only if reliable information on local ground properties is available.

In order to determine resonance frequencies and amplification factors for an arbitrary site in a predictive model, it is obvious that global, macro-seismic data like general soil classes, magnitude scales and source-to-site-distance are not useful, because there are no evident significant dependencies. Therefore, in order to set up a reliable prediction of seismic load with respect to local amplification, it is fundamentally necessary to complement the general model by information about the local resonance system. This is a field of engineering seismology with many research activities in recent years, e.g. Nakamura's spectral H-V-ratio method, aftershock and micro-tremor analyses. We have also developed a new approach to predict the probability distribution of the fundamental modes of resonance of layered soil with randomly varying layer thickness and wave velocity, together with the corresponding amplification [24].

For the average energetic input of the strongest resonance, described by the intensity parameter S_0 of the corresponding Kanai-Tajimi-Spectrum, an exponential decay with hypo-central distance was expected, attributed to general, spatial attenuation with some variability due to non-isotropic radiation from the source, propagation path effects and possibly stronger deviations at certain sites from the layered soil model as generally assumed. S_0 cannot be expected to satisfy the same geometrical attenuation laws ~1/HD and ~1/√HD known from empirical analyses of PGA values, because S_0 is an actual measure for energy, while PGA is not. Indeed, clear dependency from hypo-central distance was found. Fig. 10displays exponential trends for the different wave phases of the load model separately for near, middle and far field records of the N94 dataset, which can, of course, just provide preliminary results with improvable statistical significance.

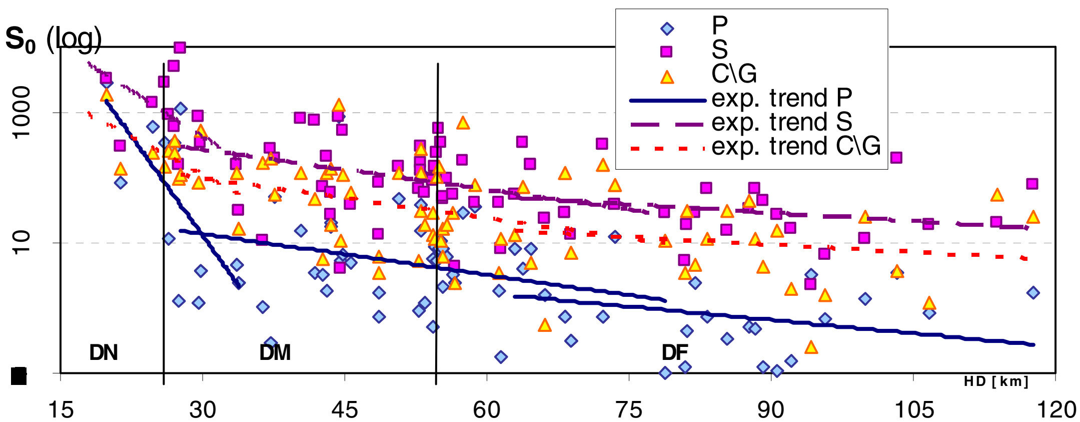

Fig. 10 Incitation S_0 corresponding to the strongest resonance frequency of the modeled wave phases versus hypo-central distance, exp. trends separately for near, middle and far field records, N94

These trends are not the same for different distance ranges, similar to well-known PGA attenuation laws, e.g. [23]. Strongest attenuation occurs in the proximity of the faulting area, with maximum descent for P waves, while in the middle and far field, the decrease of S_0 is similar for all wave phases.
Trend levels have significant order for the different wave phases, which lines up with physical properties of the corresponding wave types. On the one hand, S waves have usually the strongest share of energy released at the rupture, while their corresponding material damping is one order lower than for P waves. Direct waves are generally stronger damped with distance than indirect, especially guided waves.
The almost identical trends of the C\G and S phase, while at different levels, may indicate that the identified resonances during the C\G phase were mostly due to indirect body and coda waves rather than genuine guided or surface waves, whose occurrence was rarely documented for that dataset. Slightly weaker attenuation than the S wave phase may be due to the fact that indirect waves are generated by body waves, which carried corresponding energy over distance, quite late, in proximity to the site.

The shape function (5) for amplitude modulation is essentially controlled by two parameters τ and c, describing occurrence and shape of the peak in the time domain, respectively, while the third parameter, maximum value κ, has been fixed by normalization. For the S and C\G wave phases, the values of c are very preliminary due to unacceptable errors in fitting the function to the data. These are due to a certain inconsistency between the method used to determine wave phases and the estimator for the evolutionary spectrum, which must be resolved by further research. For the P wave phase, a reasonably wide range of the shape parameter c was determined, depending via τ on the relative duration of the wave phase. Short peaks of up to 3 seconds build-up are described by values in the range of 1e±3, while longer resonance build-up can be described by values of c in the range of 1e–6 to 1e–12

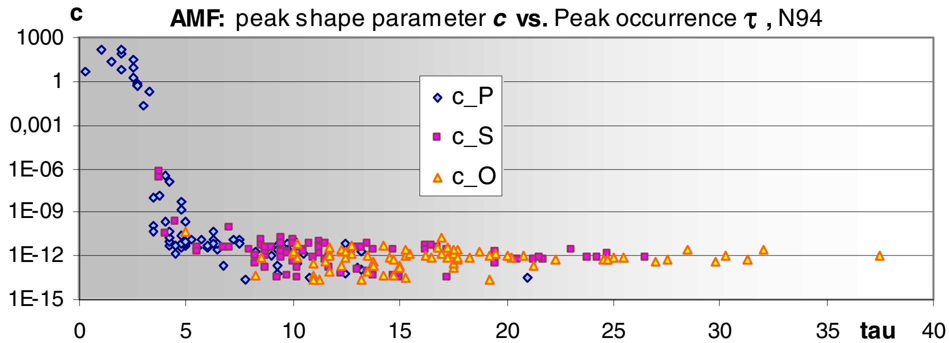

Fig. 11 Peak shape parameter *c* of AMF (5) versus peak occurrence τ of the modeled wave phases, N94 dataset. In the P wave phase (diamonds), LSQ fits to approximations were realistic and hence results for c_P are reliable, showing a clear connection between both parameters.

AMF-Parameter τ clearly reflects prolongation and increasing decomposition of wave phases with increasing distance to the source (see Fig. 12). Nevertheless, it turned out that in order to model shape characteristics of all wave phases by similar rules for τ, an additional parameter for the beginning of the wave phase should be introduced, turning τ into build-up duration of the corresponding peak. Due to certain inconsistencies between the evolutionary spectral and principal axis estimates, problems occurred with non-linear least squares fitting which could not be straightforwardly solved in that first proposal and are left for further research.

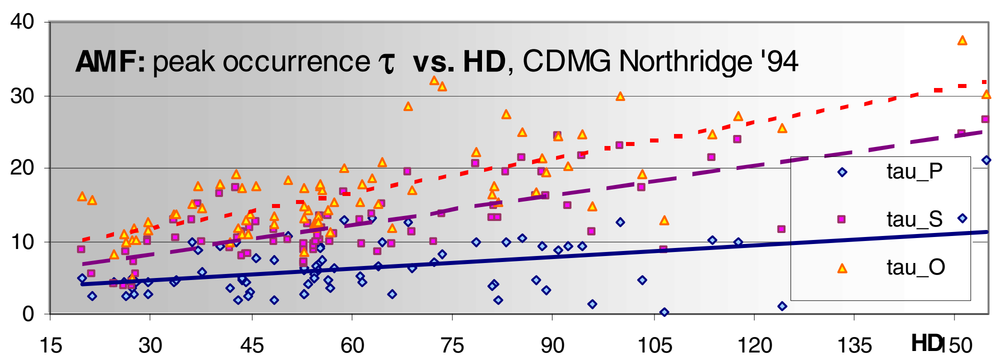

Fig. 12 Peak occurrence τ of AMF (5) vs. hypo-central distance for the dataset of N94 and the three wave phases of the load model (1)

Estimated load models have also been verified by comparison of average velocity response spectra of simulated time series. The results show that the load model is consistent in terms of the RSP method. Moreover, the most important feature of modeling fundamental resonances is reflected clearly in the RSP of the estimated load models. This is, together with the reference component, a substantial improvement.

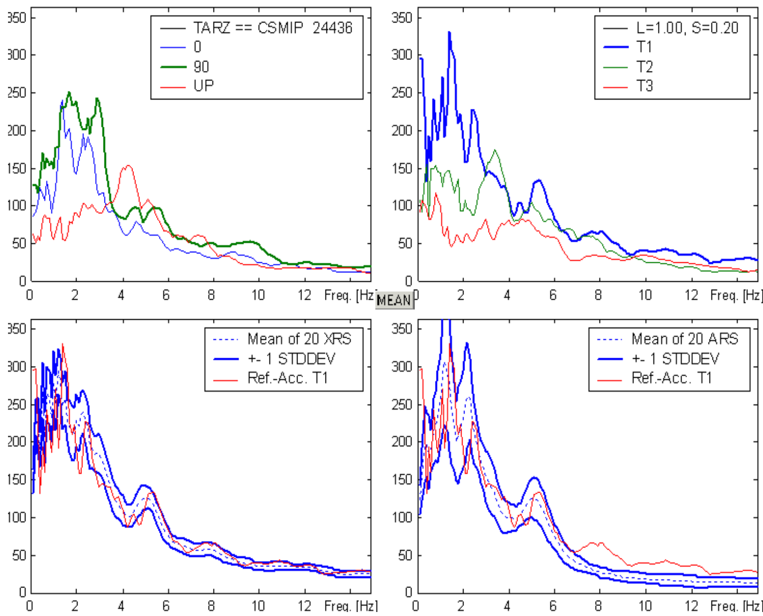

Fig. 13 Velocity response spectra with 5% damping of the original components and components transformed onto time-dependent stochastic principal axes (upper left and right), Average vel. response spectrum of a sample of 20 time histories for the intermediate steps of load approximation and least-squares fitting (bottom left and right, resp.), each of the latter re-normalized at the total energy of the evol. spectrum of the reference component T1, N94, TARZ (near field with hill resonance).

DISCUSSION

The proposed, parametric evolutionary load model represents the base of a new approach to seismic hazard assessment, which takes into account transient and other wave characteristics of seismic ground acceleration and the influence of local soil conditions as well. Which load level is expected to be attained by which wave type in which range of frequency?

To answer this question is the essential goal of the proposed load model, which provides explicit means to take into account the physical characteristics of seismic waves most relevant for building damage. This is accomplished in a feasible way by a restricted set of physically transparent parameters which relate to both micro-(local) and macro-seismic parameters.

By a comparative study of three strong earthquakes in the Los Angeles metropolitan area, recent results by other authors have been confirmed which indicate that local resonance and certain (sub)surface topographic geometries play a decisive role in the distribution of damage at strong earthquakes and hence need to be explicitly addressed in load prediction for seismic hazard assessment and aseismic design. These results are strong evidence of the invariance of resonance frequency bands in local strong ground acceleration and the dominance of local amplification over source and propagation path characteristics.

Significant differences of the range of parameters for P, S and C\G wave phases underline, besides strong directional characteristics expressed by the course of the time-dependent stochastic principal axis, the need to consider major fields of different wave types as separate, stochastic processes relevant for seismic load on buildings and lifelines.

In order to provide means to determine the predictive relations of the model parameters, an estimation procedure based on data of previous earthquakes has been proposed and verified. It includes steps of determining a reference component, identifying phases of wave type dominance, approximating relevant load in the evolutionary spectrum of the wave phases and least-squares fitting non-linear shape functions.

Physical significance of the model parameters and shape functions has been demonstrated. Some rely to macro-seismic parameters and can be determined by global scaling and attenuation laws, others are strongly locally bound and must be directly determined by recorded data at the site of interest or sites with similar resonance regime. Methods like micro tremor analyses or artificial shock waves may turn out to be useful for this purpose. In order to transfer this empirical information into the proposed model, stochastic models of the local soil layer resonance regime should be taken regard of, e.g. [24].

The aspired 3D predictive load model is not yet complete with this proposal. It must be complemented by a parametric model for the 3D course of the time-dependent stochastic principal axis (component correlation), in order to introduce into the prediction the strong directional characteristics of the dominant wave types, which inflict different and interdependent damage to the building. Stability of this principal axis has been verified in [6]. The shape function for amplitude modulation with time must be enhanced for better fitting to S and C\G wave phases.

Modelling just three wave fields by one dominant peak of the evolutionary spectrum each means simplification of reality and hence a modelling error. This modelling error has been stepwise localised and quantified during the estimation procedure for the load model. During the approximation step, there is a systematic and intended loss of non-relevant load shares which can be balanced by correction factors. Besides that, there are additional estimation errors, if there are more resonance peaks with similar amplitude in the same wave phase, which are inevitably neglected by the chosen approach.

A more sophisticated wave phase model with more wave phases may be useful for load analysis and special cases with very high sensitivity, but it would be impractical for general predictive purposes. At the current state of research, the methods for the identification of wave dominance phases and separation of multiple, overlaid wave fields are not yet sufficient.

In general, the statistical base should be broadened to improve the reliability and the range of applicability of the current results. Explicit terms for scaling relations and design rules must be developed and results compared with state-of-the art predictions according to UBC and other regulations.

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