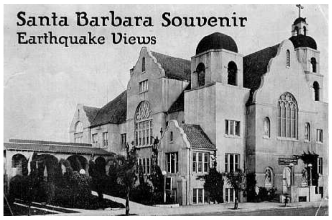

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EFFECTS OF TOPOGRAPHIC POSITION AND GEOLOGY ON SHAKING DAMAGE TO RESIDENTIAL WOOD-FRAME STRUCTURES DURING THE 2003 SAN SIMEON EARTHQUAKE, WESTERN SAN LUIS OBISPO COUNTY, CALIFORNIA

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ABSTRACT

The California Geological Survey, sponsored by the California Earthquake Authority, recently completed a study of earthquake shaking damage to residential wood frame buildings caused by the 2003 M6.5 San Simeon earthquake (McCrink, et al, 2010). The results of this study reveal that earthquake shaking damage to wood frame structures, in terms of relative frequency of occurrence (damage rate) and normalized loss (damage severity), depends on complex interactions and combined effects of topographic, geologic and structure factors. Both the rate and severity of damage, independent of structure type, is significantly greater on hilltops compared to hill slopes when underlain by older, indurated sedimentary rocks. This increase in damage is interpreted to be the result of topographic amplification. An increase in the damage rate is found for all structures built on Plio-Pleistocene alluvial deposits (Paso Robles Formation) independent of topographic position, and this is interpreted as the result of amplified shaking caused by geologic site response. Observations showing greater damage to structures with otherwise shaking-resistant characteristics suggest a spectral response to topographic amplification.

Several issues need to be resolved before simple predictive parameters can be developed for use in loss estimation and insurance underwriting. Improved methods are needed to distinguish areas susceptible to topographic amplification, geologic site response and/or combined shaking effects. Improved seismological modeling may resolve questions about the effects of hilltop shape. Because the dataset used in this study is limited in size, the results of this study should be validated with a more robust dataset of earthquake shaking damaged houses.

PURPOSE AND METHODOLOGY

This study uses a relatively small but comprehensive dataset of earthquake damage claims prepared by the California Earthquake Authority (CEA) following the 2003 San Simeon earthquake, to document whether topographic amplification occurred and was a major contributor to both the number of earthquake insurance claims and the cost of shaking-related damage. The primary question this study set out to answer is:

- Can a statistically significant case be made that shaking damage caused by the San Simeon earthquake to wood-frame houses built on hilltops is greater than damage to houses built on hill slopes or flatlands?

In order to isolate topographic effects from other contributors to damage in a manner useful for loss estimation, three additional questions were posed:

- Can observed damage on hilltops be explained by differences in structural characteristics of houses rather than their topographic position?
- Can observed damage on hilltops be explained by differences in underlying geologic materials?
- Can a simple, readily attainable factor be found that captures, in a general way, the complexity of topographic/geologic site effects on potential earthquake shaking and consequent damage a-priori?

To answer these questions, a study area in western San Luis Obispo County was delineated to include the majority of damage from the San Simeon earthquake (Study area shown in Fig. 1), and classical post hoc statistical analysis was used to assess the contribution of various factors to observed damage to wood-frame houses. The factors considered as contributors to earthquake shaking damage in this study are topographic characteristics, underlying geologic materials, structural characteristics, and estimated level of ground motion. The measure of earthquake shaking damage change is defined as having two components when comparing one factor to another: 1) increased rate or frequency of damage occurrence among houses, and 2) increased severity or normalized loss to individual structures given that damage has occurred.

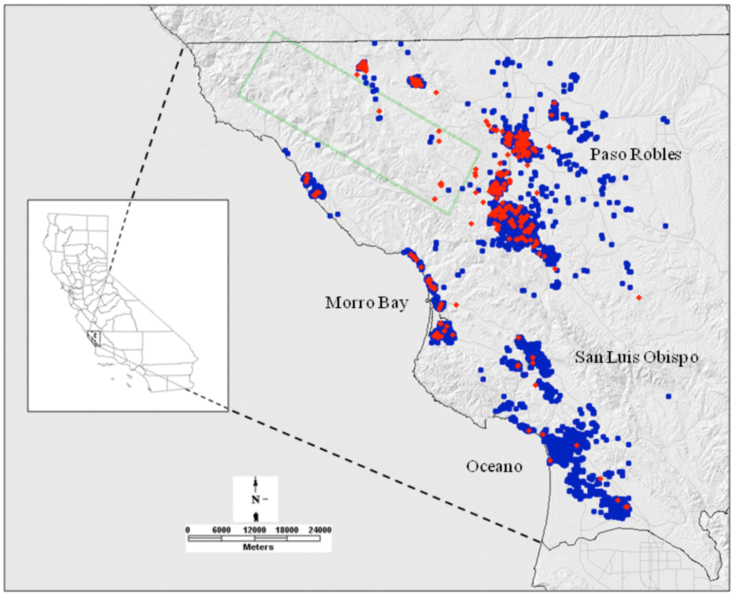


Fig. 1. Study area location in western San Luis Obispo County; larger communities are labeled. Small blue dots show locations of houses with earthquake insurance and red dots show locations of houses where claims were filed. The inclined green rectangle in the upper left is the approximate surface projection of the seismic source.

To address the first measure of damage change, relative frequency counts of houses damaged (percentage of houses reporting damage claims) were used, stratifying damage data by the subject factors. With this approach, significant results can provide an estimate of the probability of damage for different topographic, geologic, and/or structural conditions. Overall, roughly six percent of the insured properties in the study area experienced enough damage to file a claim, which serves as a baseline for comparing the effect of the different factors under study.

A more quantitative approach is taken for the second measure of change, by identifying associations and/or differences in damage costs as related to the factors under study. For the CEA dataset, damage costs associated with an insurance claim include both structural and non-structural damage. To account for the effect of differing house value and size on loss, the dollar value of each damage claim was normalized by dividing it by the insured value of the house. As a reference point, the median value of normalized loss for wood-frame houses caused by the San Simeon earthquake is 0.075, or 7.5 percent of the insured value. Non-parametric statistical tests, primarily Kruskal-Wallis and Mann-Whitney rank sum tests were used to analyze the quantitative economic damage data, which are highly skewed and inappropriate for analysis by conventional parametric statistical methods. In these tests, nominal-scale (categorical) variables, here damage factors, are ranked on the basis of a ratio-scale variable, normalized loss, to test the null hypothesis that the group medians are separate estimates of the same population. The alternate hypothesis, when the test statistic equals or exceeds the critical value and the probability of the null hypotheses is less than 5 percent ($p\text{-value} < 0.05$), is that the medians are significantly different.

SHAKING DAMAGE BASED ON GEOLOGY AND TOPOGRAPHIC POSITION

Early analyses considered only topographic position and underlying geology, without considering structure characteristics, to determine what effects these parameters had on building damage. There is a pronounced increase in the damage rate for houses on Hilltops underlain by Cretaceous or Tertiary rocks (Fig. 2). Houses on Plio-Pleistocene Rocks show a similar but more subdued damage rate trend for topographic positions and, because all are about twice the baseline damage rate of six percent, it appears that these rocks are also experiencing amplification due to geologic site response, such as that caused by the presence of low-velocity surface materials. There appears to be geologic site amplification occurring on Tertiary rocks as well, relative to Cretaceous rocks, with a 1.5 to 2 fold increase in damage rate for the corresponding topographic position.

Table 1. Factors and variables evaluated in this study. The primary variables evaluated in terms of damage rate and damage severity either exist as or were transformed into categorical groups.

FACTORS AND VARIABLES EVALUATED					
FACTORS AND VARIABLES	**VARIABLE CATEGORICAL GROUPS**				
TERRAIN:					
Topographic Position	Hilltops	Slopes	Plains		
Slope Gradient (%)	0 to 5	5 to 10	10 to 15	15 to 20	> 20
Slope Curvature	< -0.5	-0.5 to 0.0	0.0 to 0.5	> 0.5	
GEOLOGIC:					
Geologic Age	Cretaceous	Tertiary	Plio-Pleistocene	Quaternary	
STRUCTURAL:					
Year Built	Pre-1980	1980’s	Post-1980’s		
Square Footage	Less than 1500 ft^2	1500 to 2400 ft^2	Greater than 2400 ft^2		
Stories	One Story	Multi-story			
Foundation	Slab	Raised			
Garage	Attached-Adjacent	Attached-Under			
Floor Plan	Rectangular	Non-Rectangular	Complex		
GROUND MOTION:					
Peak Acceleration	Less than 20 % g	20 % to 30 % g	Greater than 30% g		
COMBINED DIRECTIONAL FACTORS:					
Slope Aspect – Source Direction	0 to 45	45 to 90	90 to 135	135 to 180	
Short Axis – Source Direction	0 to 30	30 to 60	60 to 90		

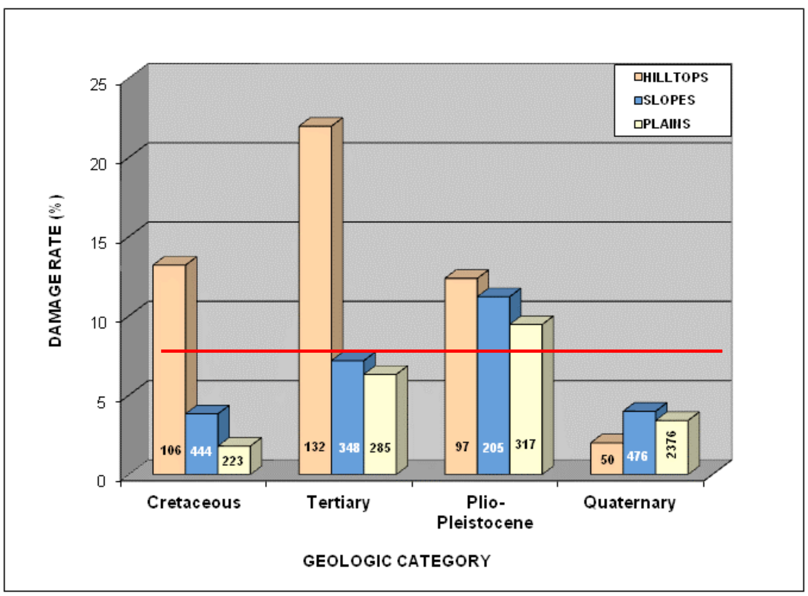


Fig. 2. Topographic amplification effects on wood-frame structures are dependent on geology – for the San Simeon earthquake it only occurred in the older, more indurated Tertiary and Cretaceous rocks, and not in poorly indurated Plio-Pleistocene or Quaternary rocks. Elevated damage for houses on Plio-Pleistocene rocks for all topographic positions suggests that these rocks are producing a geologic site response effect. The numbers on or above the bars represent the number of houses with earthquake insurance used to derive the damage rate. The red line represents the overall damage rate for all claims in the study area (~6%).

The patterns of earthquake shaking damage severity (Normalized Loss) mimic those of damage rate (Fig. 3). The test statistic exceeds the critical value for houses on Tertiary rocks, indicating that houses on hilltops experienced significantly greater damage than those on slopes or plains. Damage severity to houses on Cretaceous rocks are also elevated on hilltops, but the statistical proof of significantly higher damage is weaker, with p-values falling between 5 and 10 percent; here termed a "borderline significance." Houses constructed on Plio-Pleistocene rocks do not show any significant differences in damage severity based on topographic position, nor is there strong evidence for increased damage on these rocks as a whole, which differs from the damage rate data.

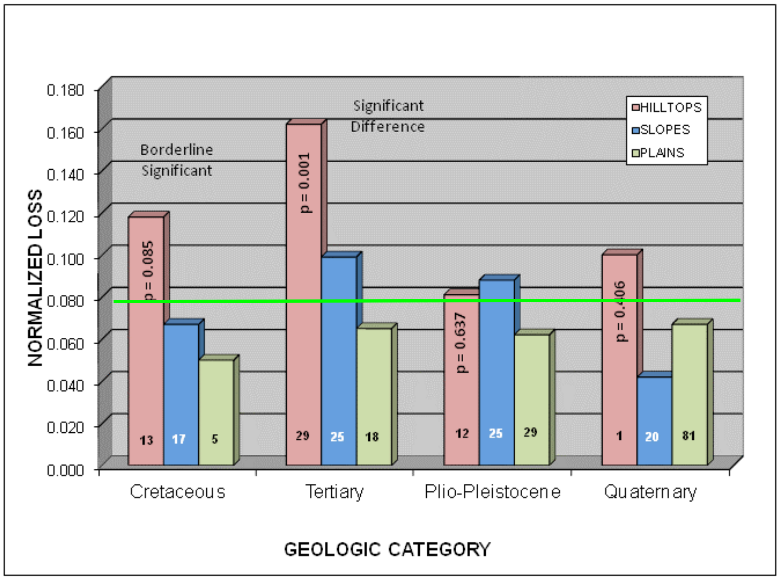


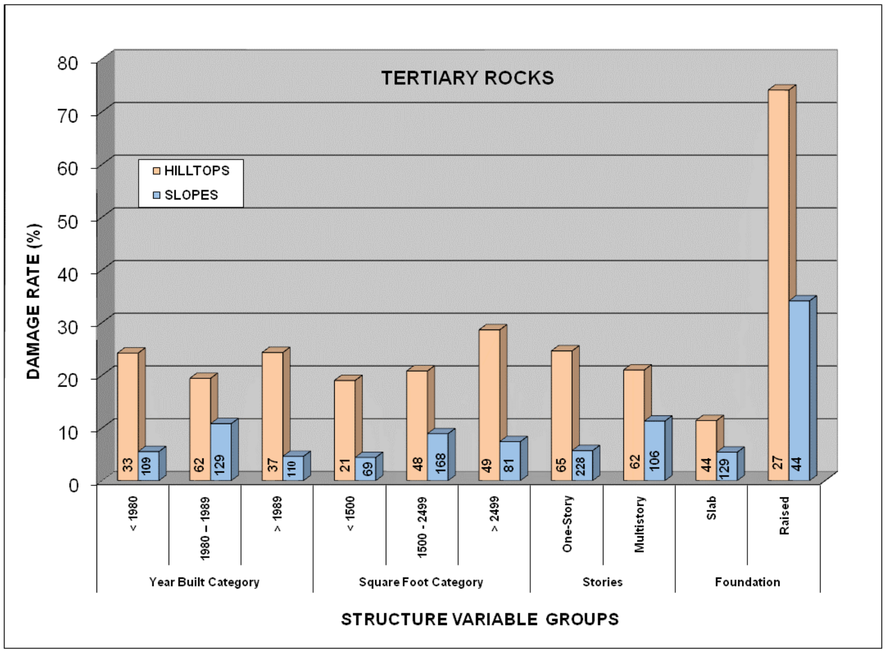
Fig. 3. Amplification-related damage severity mimic the damage rate, with higher median damage to houses on hilltops underlain by Tertiary and Cretaceous rocks. Statistical analyses indicate that damage severity is significantly higher on hilltops underlain by Tertiary rocks, and borderline significantly higher (p-value lies between 5 and 10 percent) on hilltops underlain by Cretaceous rocks compared to houses on slopes or plains. Severity is measured by normalized loss, which is the amount of the insurance claim divided by the insured value of the house. The height of the bars represents the median value of normalized loss. The number on or above each bar represents the number of insurance claims, and the inserted p-value is the result of the statistical test for differences in median normalized loss. If a p-value is not present the data were considered too sparse for valid results. The green line represents the median normalized loss for all earthquake insurance claims in the study area (0.075).

SHAKING DAMAGE BASED ON GEOLOGY AND TOPOGRAPHIC POSITION WITH STRUCTURAL FACTORS CONSIDERED

Incorporating the structure variables resulted in a data correlation problem – houses on hilltops and houses on plains are too different to be considered random samples from the same population – and a data size problem – too few samples of hilltop houses on Quaternary rocks, and too few plains houses on bedrock. As a result, the final analyses considered only houses on hilltop and slope topographic positions, and on Cretaceous, Tertiary and Plio-Pleistocene rocks.

Increased damage rate on hilltops compared to slopes remains apparent when structural variables are considered and the underlying geologic materials are Tertiary or Cretaceous in age (Fig. 4). Damage rates are 2 to 3 times greater on hilltop houses than for houses on slopes, independent of structural characteristics. Again, damage rates to houses on Tertiary rocks are 1.5 to 2 times greater than to those on Cretaceous rocks for all structural variables. As would be anticipated from previous figures, houses built on Plio-Pleistocene rocks experienced more than the baseline damage rate of about six percent for all structure types, yet show little change in the rate of damage between hilltops and slopes.

On Tertiary rocks, statistically significant higher damage severity are observed for the oldest houses, intermediate-size houses, one story houses, houses with slab foundations, and those with garages adjacent to living space (no soft story effect expected)(Fig. 5). On Cretaceous rocks, significantly higher damage is found for one story houses, and borderline significant (p-value lies between 5 and 10 percent) higher severity is observed for intermediate-size houses and houses with adjacent garages. With the exception of increased damage to older houses on hilltops, the elevated damage severity to houses on hilltops with damage-resistant characteristics is unexpected. The inferred shorter natural period of the structures damaged on hilltops – those with smaller size, slab foundation, one story or no garage under living space - suggests that the ground motions associated with topographic amplification have a shorter predominant period than the ground motion on slopes.



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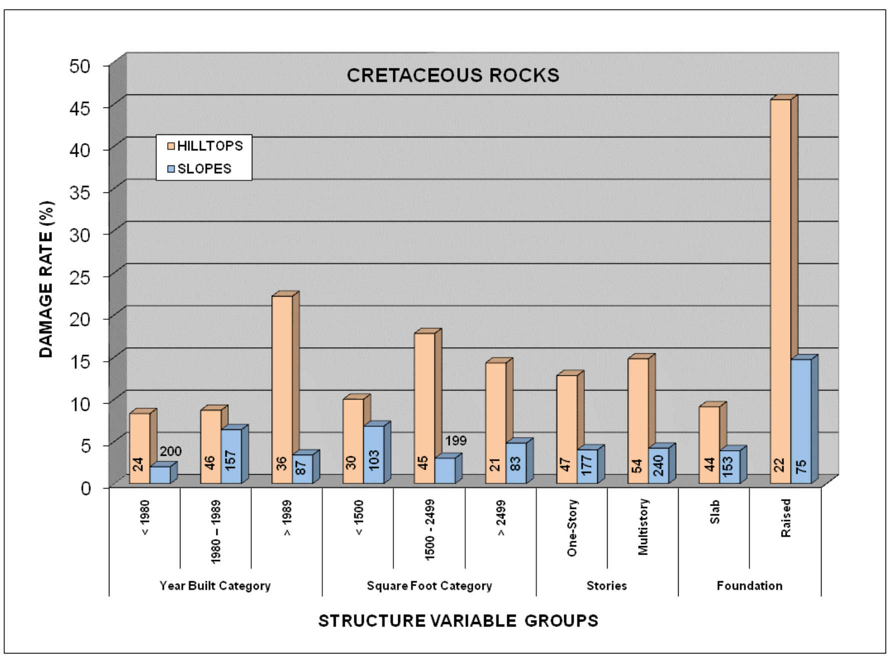
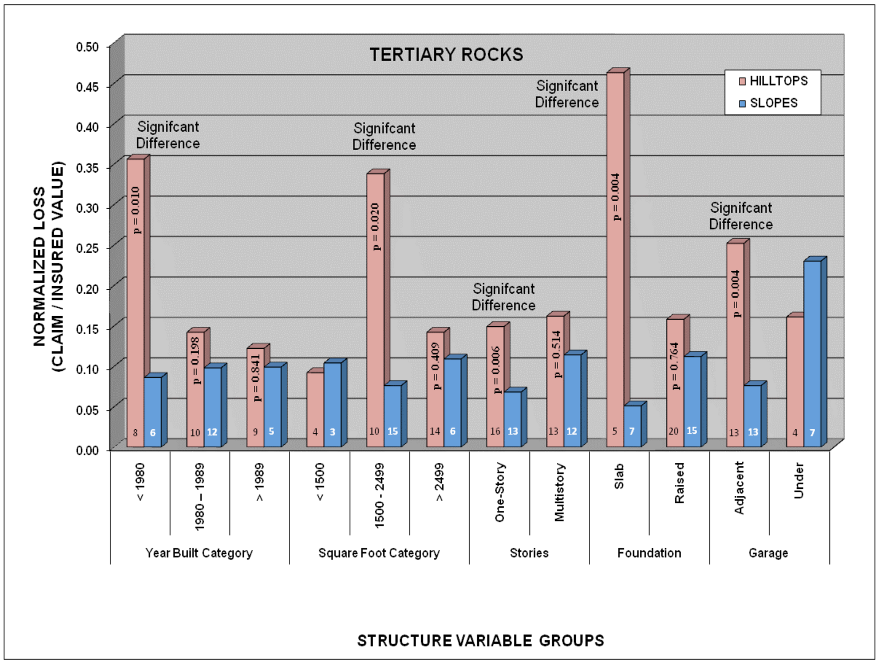


(b)

Fig. 4. Earthquake shaking damage rate for the topographic position variable for houses on Tertiary rocks (a) and Cretaceous rocks (b), stratified by the structure variable groups. Damage rate is consistently higher for hilltop houses for all structure variables. Damage rate for houses on Tertiary rocks is also nearly twice the rate for houses on Cretaceous rocks (b), suggesting that additional amplification is occurring for these rocks.



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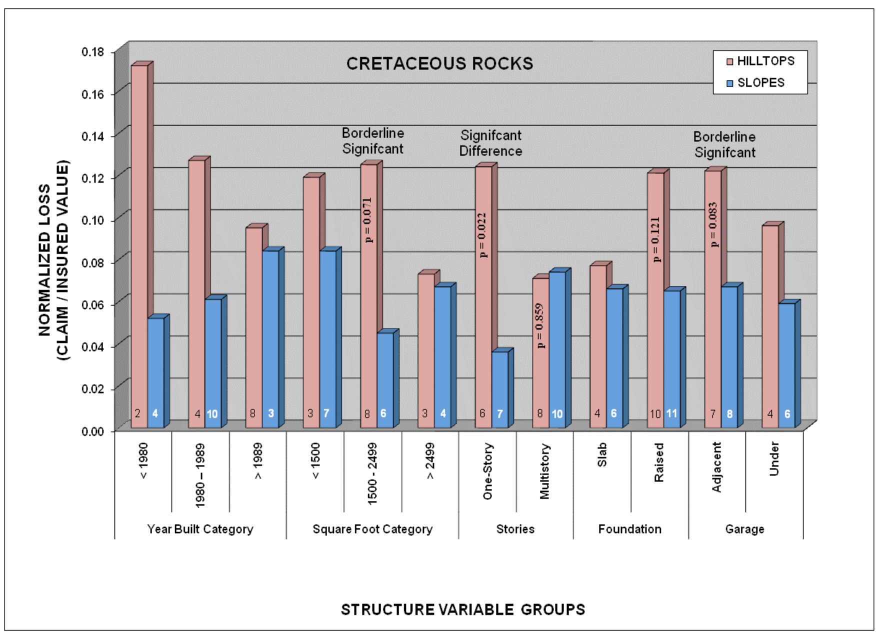
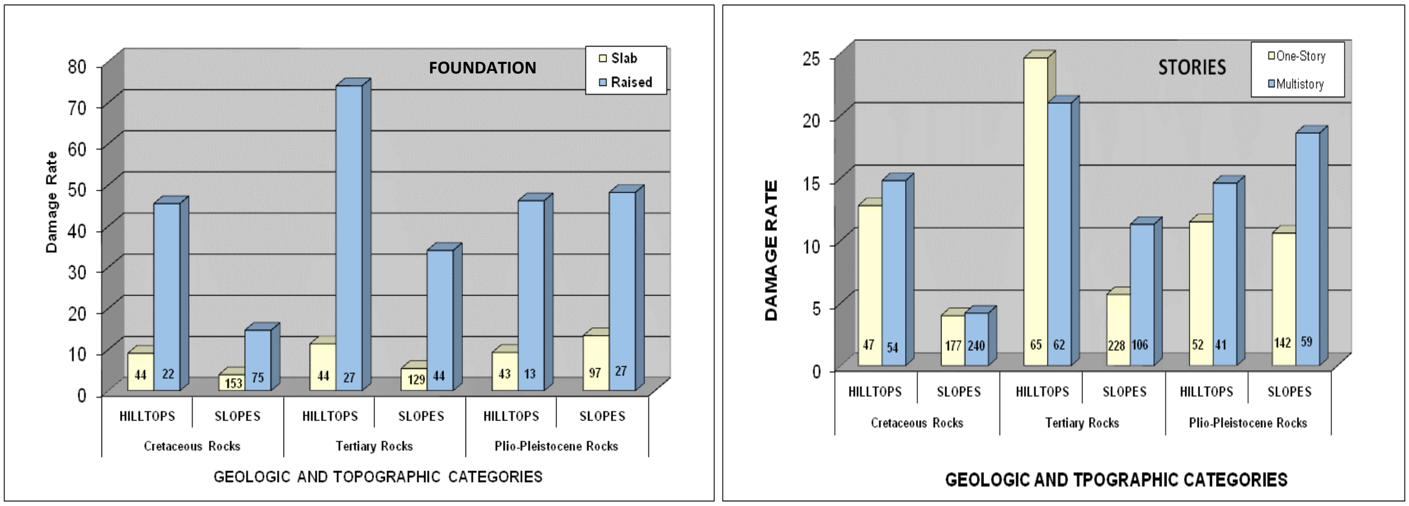


(b)

Fig. 5. Earthquake damage severity for the topographic position variable for houses on Tertiary rocks (a) and on Cretaceous rocks (b), stratified by the structure variable groups. For houses on Tertiary rocks, damage severity is significantly higher on hilltops for the oldest houses, intermediate size house, one story houses, houses with slab foundation, and those with garages adjacent to living space. Hilltop houses on Cretaceous rocks show a similar pattern of damage, but statistical significance is only found for one story houses.

SHAKING DAMAGE FROM THE PERSPECTIVE OF THE STRUCTURAL CHARACTERISTICS

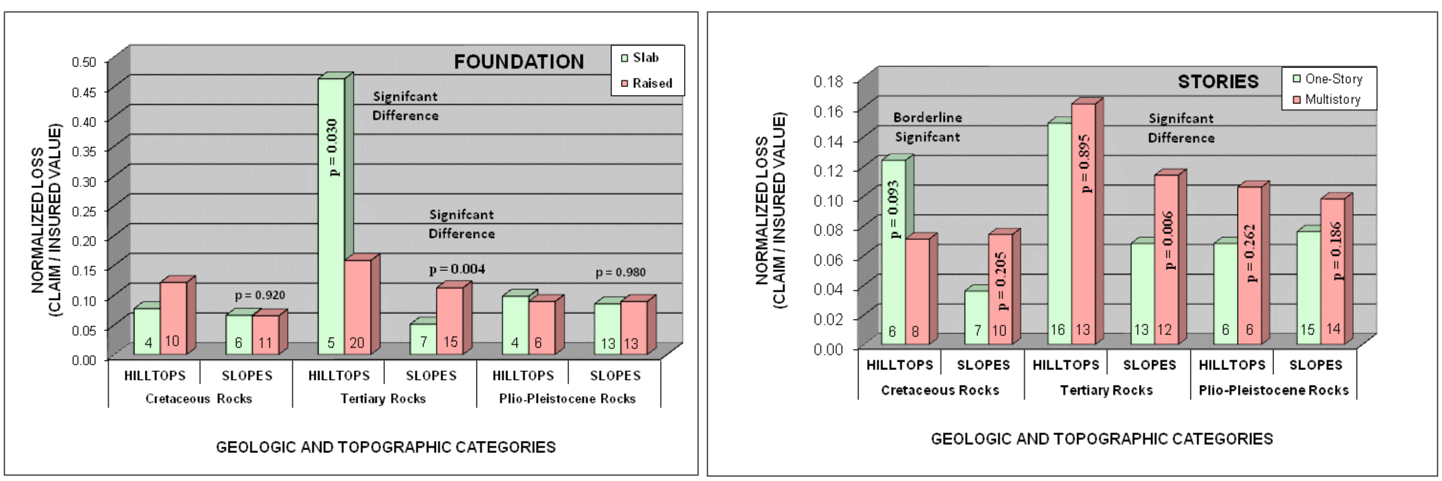
The most significant structural variable in terms of damage rate is foundation type, where houses with raised wood floor foundations have 4 to 7 times more frequent damage than houses with concrete slab foundations, independent of geologic or topographic factors (Fig. 6). All other structural variables (e.g. stories) have less influence on damage rate than geology and topographic position.



(a) (b)

Fig. 6. Earthquake shaking damage rate for the foundation (a) and stories (b) structural variables stratified by geologic and topographic variable groups. Damage rate is consistently higher for houses with raised foundations versus slab foundations independent of geologic and topographic conditions. Multistory houses are more frequently damaged on slopes of Tertiary or Plio-Pleistocene rocks, but this structural characteristic is not as important to damage rates as topography or geology, and this observation can be said for the year built and square footage variables as well.

The foundation type variable has only significantly higher damage severity for houses built on Tertiary rocks, and exhibits a reversal in severity from raised foundations on slopes to slab foundations on hilltops (Fig. 7). A similar but less pronounced trend is observed for the Stories variable where multistory houses on Tertiary rock slopes have significantly greater damage than one story houses, while on hilltops both structure types have increased damage without much difference between them.



(b) (b)

Fig. 7. (a) Earthquake damage severity for the foundation structure variable, stratified by geologic and topographic position variable groups. Houses with raised foundations only show significantly higher damage severity on Tertiary rock slopes, while houses with slab foundations show significantly higher damage severity on Tertiary rock hilltops. Insufficient numbers of cases for hilltop houses on Cretaceous and Plio-Pleistocene rocks precluded valid statistical tests and no p-value is reported. (b) Earthquake damage severity for the stories structure variable, stratified by geologic and topographic position variable groups. Multi-story houses on Tertiary rock Slopes have significantly higher damage severity, while One Story houses on Tertiary rock Hilltops have almost identical damage to multi-story houses and both have elevated damage. One Story houses on Cretaceous rock Hilltops have a borderline significant (p-value lies between 5 and 10 percent) higher damage than Multi-story houses.

KEY OBSERVATIONS

1. DAMAGE TO WOOD-FRAME HOUSES DUE TO TOPOGRAPHIC AMPLIFICATION IS QUANTIFIABLE, AND WAS SIGNIFICANTLY GREATER COMPARED TO HOUSES ON SLOPES
    - Clear comparisons of damage to houses on hilltops and plains topographic positions could not be completed because of correlations in the data – houses on hilltops and houses on plains are too different to be considered random samples from the same population.
    - Damage rate to hilltop houses is 2 to 3 times higher than to houses on slopes, independent of structural characteristics.
    - Where differences in damage severity are statistically significant - for houses with certain structural characteristics - losses for hilltop houses are 2 to 3 times greater than houses on slopes.
2. HOUSES WITH SOME TYPICALLY FAVORABLE CHARACTERISTICS EXHIBIT GREATER DAMAGE SEVERITY ON HILLTOPS
    - These include houses with slab foundations, one story houses, and houses with garages adjacent to living space.
    - The inferred shorter natural period of the structures damaged on hilltops suggests that the ground motions associated with topographic amplification have a shorter predominant period than the ground motion on slopes.
3. TOPOGRAPHIC AMPLIFICATION EFFECTS ARE DEPENDENT ON GEOLOGY – IT IS NOT OBSERVED IN YOUNGER ROCKS
    - The natural erosional patterns of poorly indurated Plio-Pleistocene and Quaternary materials may prevent the development of topographic features with dimensions of significance to the incident seismic shaking.
4. DAMAGE RATE AND SEVERITY ARE GREATEST TO HOUSES BUILT ON TERTIARY ROCKS ON HILLTOPS
    - Field observations and slope curvature measurements indicate erosional patterns on Tertiary rocks favor steep-sided, narrow ridges suggesting ridge shape may enhance the focusing of seismic waves at the top of a ridge or hill.
    - Development of narrow ridges in Tertiary rocks may allow the ridge to oscillate, much like a tall building, in response to strong shaking.
    - Shear wave velocity measurements on similar rocks in the Los Angeles area suggest deep weathering profiles forming a low-velocity layer within ridges can produce a geologic site response.
    - More than one of the above might be occurring simultaneously.
5. HOUSES WITH RAISED FOUNDATIONS WERE DAMAGED 4 TO 7 TIMES MORE FREQUENTLY THAN HOUSES WITH SLAB FOUNDATIONS, INDEPENDENT OF GEOLOGY OR TOPOGRAPHY
    - The flexibility of raised wood floor/perimeter footing systems is known to allow more internal movement, which in turn results in damage to components typically covered by earthquake insurance (framing, drywall/plaster, tile, counters, etc.).
    - The other structural variables considered in this study do not affect damage as significantly as geology and topography.

WHERE DO WE GO FROM HERE?

One of the goals of this study was to see if parameters could be developed that would predict where topographic amplification would occur and the magnitude of shaking damage that could be expected. However, this study indicates that multiple effects may be occurring on hilltop sites underlain by Tertiary rocks. In order to move forward with the development of damage prediction parameters for topographic amplification we need to isolate the causes of enhanced damage to houses on hilltops underlain by Tertiary rocks. The potential for a low velocity layer in the Tertiary rocks can be assessed by geophysical methods on ridges where elevated damage occurred in the San Simeon earthquake. The effects due to steep-sided, narrow topographic shapes can be assessed by modeling.

The topographic modeling program used in this study was valuable because of its simplicity and its ability to consider small topographic features in a regional context, but a number of data points were lost to the analyses due to ambiguous topographic position determinations. A more sophisticated topographic model can be developed that eliminates this ambiguity, considers feature dimensions relative to the incident seismic wavelength, and includes a measure of slope curvature if hilltop shape is found to be an important contributor to damage.

REFERENCE

McCrink, T.P., C.J. Wills, C.R. Real, and M.W. Manson [2010], "Effects of Topographic Position and Geology on Shaking Damage to Residential Wood-Framed Structures during the 2003 San Simeon Earthquake, Western San Luis Obispo County, California", Earthquake Spectra, Vol. 26, No. 3, pp. 770-802.