ENHANCED RAPID VISUAL SCREENING (E-RVS)

METHOD FOR PRIORITIZATION

OF SEISMIC RETROFITS IN OREGON

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EXECUTIVE SUMMARY

Overview

FEMA’s rapid visual screening (RVS) procedure was developed to identify, inventory, and rank buildings that are potentially seismically hazardous. The RVS procedure was published in 1988 (FEMA, 1988a) and has been widely used throughout the United States to evaluate thousands of buildings. The RVS procedure was updated in 2002 (FEMA, 2002a) to incorporate technical advancements in earthquake engineering and seismic hazard analysis.

RVS Final Scores are a quantitative measure of the degree of life safety risk posed by a building and are useful in the evaluation of life safety risk and in the prioritization of seismic retrofit programs for populations of buildings. The RVS procedure was designed to be the preliminary screening phase of a multi-phase procedure for identifying potentially hazardous buildings. Buildings identified as potentially hazardous by the RVS procedure should be analyzed in more detail by an experienced seismic design professional.

Technical Review of the Rapid Visual Screening Methodology

This report reviews the technical underpinnings of the RVS procedure, with emphasis on the mathematical relationships between RVS scores and the probabilities of building collapse, use of several types of seismic hazard data, and suggestions for using RVS Final Scores for initial prioritization of seismic retrofits for a large population of public educational buildings in Oregon.

Our technical review of the existing RVS methodology has concluded that:

1) The use of seismicity regions, rather than site-specific seismic hazard data, for the RVS procedure substantially reduces the accuracy of RVS results. This conclusion holds for either of the two RVS seismic hazard methods (using the seismicity region maps by county or determining the seismicity region from site-specific data). As shown by examples, the variation in probability of collapse at the site-specific Maximum Considered Earthquake (i.e., at 2/3ds of the 2% in 50 year ground motion) varies by at least a factor of 8 within a single county and by factors of at least 20 to 60 for the moderate and high seismicity regions overall; none of this variation is considered by the existing RVS methodology. The definition of the MCE as 2/3rds of the 2% in 50 year ground motion conforms to the usage in the RVS calculations (cf. Section 6.2 in FEMA (2002b)). 2) In some cases, the combinations of RVS Score Modifiers result in Final

Scores which are mathematically out of bounds: the Final Scores correspond to probabilities of reaching the complete damage state or probabilities of collapse which exceed one. These irregularities in Score

Modifiers affect the relative risk assigned to various buildings (i.e., the Final Score) and also affect which buildings are deemed to be above or below any defined cut-off score and thus directly affect the buildings for which additional study is recommended. 3) The RVS Score Modifiers for Soil Types C, D, and E appear to substantially overcorrect for soil effects in comparison to the soil factors in the 2003 International Building Code (International Code Council, 2002).

4) The logarithmic relationship between Final Scores and the probability of collapse makes RVS results somewhat difficult to interpret, especially for less technical users.

In combination, the above limitations of the existing RVS methodology, most dramatically the use of seismicity regions which encompass broad ranges of seismic hazard levels, substantially limit the accuracy of RVS results.

From a public policy perspective, the use of seismicity regions in the RVS procedure produces inaccurate results: seismic risk is systematically overestimated for locations with local MCEs below the median values for a seismicity region and seismic risk is systematically underestimated for locations with local MCEs above the median values for the seismicity regions. This oversimplification in the RVS procedure is not corrected by using local seismic hazard data to determine the appropriate RVS seismicity region.

To the extent that RVS scores are used to evaluate populations of buildings and to prioritize detailed evaluations and seismic retrofits, these limitations of the existing RVS procedure will result in substantially less than optimum allocation of mitigation funds and risk reduction actions. The RVS results will tend to over-encourage retrofits in lower hazard areas and to under-encourage retrofits in higher hazard areas, within a given RVS seismicity region.

DOGAMI E-RVS Method: Enhancements to RVS To improve the accuracy and usefulness of RVS results, we have developed an enhanced RVS methodology called the E-RVS methodology. Using the E-RVS method, CODA and LSRI scores are derived, where CODA means Complete Damage and LSRI means Life Safety Risk Index. The E-RVS method:

1) Improves the accuracy of seismic hazard data by using site-specific MCEs rather than median MCEs for broad seismicity regions, 2) Reduces the

effects of out of bounds RVS Final Scores, by avoiding interpretation of RVS Final Scores which are not physically meaningful (i.e., the Final Score must correspond to the probability of the complete damage state < 1.0), 3) Adjusts the RVS soil-rock Score Modifiers to yield results which are consistent with the 2003 IBC (International Code Council, 2002) soil factors.

4) Makes results easier to understand by non-technical users by using linear rather than logarithmic scales for results.

Example printouts of E-RVS results developed using the Oregon Seismic Hazard Calculator and the Oregon E-RVS calculator are provided.

The DOGAMI E-RVS methodology makes improvements in the RVS Methodology, but does not address all of the areas where improvements can be made. In the final section of this paper, we make specific suggestions for further enhancements to the RVS and E-RVS methodologies.

The Oregon University System funded the development of the E-RVS method.

1.0 Rapid Visual Screening Procedure

1.1 Overview and Concepts

The Rapid Visual Screening (RVS) procedure was developed by the Federal Emergency Management Agency (FEMA) to identify, inventory, and rank buildings that are potentially seismically hazardous. FEMA's RVS procedure was first published in two volumes in 1988 as FEMA 154 and FEMA 155 (FEMA, 1988a and 1988b). In the nearly 20 years since its publication, RVS has been widely used to evaluate thousands of buildings in many seismically active regions of the United States.

The RVS procedure was developed for a broad audience, including building officials and inspectors, and both public- and private-sector building owners. The RVS procedure was designed to be the preliminary screening phase of a multi- phase procedure for identifying potentially hazardous buildings. Buildings identified as potentially hazardous by the RVS procedure should be analyzed in more detail by an experienced seismic design professional.

RVS uses a method based on a "sidewalk survey" of a building: visual inspection of the building from the exterior and, if possible, from the interior to identify the primary structural lateral load resisting system(s) and structural materials of the building. Because RVS is designed to be performed from the street, with interior inspection not always possible and structural details not always evident without plan inspection or field testing, hazardous details will not always be visible and some seismically hazardous buildings may not be identified as such. Conversely, some buildings initially identified by RVS as potentially hazardous may prove to be seismically adequate upon more detailed evaluation.

The RVS procedure assigns a Basic Structural Hazard Score to a building, based on the identified primary structural lateral load resisting system and on the seismicity region defined for the county in which a building is located. Then, the Basic Structural Hazard Score is modified by several Score Modifiers which are related to seismic performance attributes of the building and the soil-rock type to obtain a Final Score. The Basic Structural Hazard Score, Score Modifiers, and Final Score are all related mathematically to the estimated probability that a building will collapse under severe ground shaking levels equivalent to those currently used for the seismic design of new buildings.

The intended use of the RVS procedure is to screen a population of buildings based on a cut-off value for the Final Score, S, which is used to divide screened buildings into two categories which are expected to:

- Have acceptable seismic performance, or
- May be seismically hazardous and should be studied further.

A RVS Final Score of 2.0 is suggested as a typical cut-off value. Mathematically, a Final Score of 2.0 means an estimated 1% chance of collapse at the defined level of ground shaking (2/3rds of the 2% in 50 year ground motion) for the seismicity region of the county in which the building is located.

1.2 FEMA 154 and 155 Second Editions

The Second Editions of FEMA 154 and 155 were published in 2002 (FEMA, 2002a and 2002b). This revision of the RVS evaluation methodology included:

1) collection of users' feedback on the RVS procedure,

2) review of updated information on the seismic performance of buildings, including a detailed review of HAZUS (FEMA, 2006 and earlier editions) fragility curves and the relationship between the RVS results and the detailed seismic evaluation procedures in FEMA 310 (FEMA, 1998) which is now superseded by ASCE 31 (ASCE, 2002),

3) a Users' Workshop to learn about the problems and successes of organizations that had used the original RVS procedure, and

4) revision and updating of the technical methods in the first editions of FEMA 154 and FEMA 155.

The Second Edition of the RVS procedure included updated Basic Structural Hazard Scores and Score Modifiers, drawing on HAZUS (FEMA, 2006 and earlier editions) fragility curves rather than on ATC-13 (ATC, 1985) damage functions, and updated the seismic hazard data. All references below to RVS, FEMA 154, and FEMA 155 apply to the second editions (FEMA, 2002a, 2002b).

1.3 Rapid Visual Screening Mathematics

The Basic Structural Hazard Scores (BSH), Score Modifiers (SMs) and the Final Score (S) are all measures of seismic damage potential for the building under evaluation. More precisely, the Basic Structural Hazard Score is defined as the negative of the base 10 log of the probability that the building will collapse at the level of ground shaking corresponding to the maximum considered earthquake (MCE): $BSH = -\log_{10} [P \text{ (collapse given MCE)}]$. (FEMA 155, Equation 6-1, FEMA, 2002b)

The definition of the MCE as 2/3rds of the 2% in 50 year ground motion conforms to the usage in the RVS calculations (cf. Section 6.2 in FEMA (2002b)). The BSH is a generic score for a type of class of building, and is modified for a specific building by Score Modifiers specific to that building to arrive at a final Structural Score, S. That is:

$S = BSH + SMs$. (FEMA 155, Equation 6-2, FEMA, 2002b)

Similarly, for a specific building,

$S = -\log_{10} [P \text{ (collapse given MCE)}]$.

Or, equivalently,

$[P \text{ (collapse given MCE)}] = 10^{-S}$.

For example, a Final Score, S, of 2.0 means that the calculated probability of building collapse at the maximum considered earthquake (MCE) is 10^{-2} or 0.01 (i.e., a 1% chance of collapse). For reference, calculated probabilities of collapse at the MCE corresponding to Final Scores between 4.0 and 0.0 are shown below in Table 1.

Table 1 Calculated Probabilities of Collapse vs. Final Score (S)

Final Score (S)	**Probability of Collapse[1]**
4.0	0.01%
3.5	0.03%
3.0	0.10%
2.5	0.32%
2.0	1.00%
1.5	3.16%
1.0	10%
0.5	32%
0.0	100%

[1] At the maximum considered earthquake (MCE)

If RVS mathematical results are interpreted literally, then a building with a Final Score of 3.0 has a factor of ten lower probability of collapse at the MCE than does a building with a Final Score of 2.0. Similarly, a building with a Final Score of 1.0 is 10 times more likely to collapse at the MCE than a building with a Final Score of 2.0.

More realistically, RVS results should be interpreted in the context of its intended purpose as a preliminary screening tool. The Final Scores are better interpreted as approximate measures of the relative risk between buildings, rather than as absolute measures of the probability of collapse at the maximum considered earthquake.

RVS Final Scores define a seismic fragility curve for the complete damage state of a building. The probability of collapse at the RVS-defined MCE and the probability of being in the complete damage state at the MCE are directly linked because RVS uses the HAZUS (FEMA, 2006) relationship between the probability of collapse and the probability of being in the complete damage state. The HAZUS (FEMA, 2006) relationship between these probabilities is summarized in Table 2 below. The same HAZUS relationships were included in earlier versions of HAZUS used in the 2002 RVS methodology.

Table 2 Probability of Collapse given the Complete Damage State (HAZUS relationship used by RVS)

Building Type	**Probability of Collapse**		
	Low-Rise	**Mid-Rise**	**High-Rise**
W1	0.03	NA	NA
W2	0.03	NA	NA
S1	0.08	0.05	0.03
S2	0.08	0.05	0.03
S3	0.03	NA	NA
S4	0.08	0.05	0.03
S5	0.08	0.05	0.03
C1	0.13	0.10	0.05
C2	0.13	0.10	0.05
C3	0.15	0.13	0.10
PC1	0.15	NA	NA
PC2	0.15	0.13	0.10
RM1	0.13	0.10	NA
RM2	0.13	0.10	0.05
URM	0.15	0.15	NA

NA: Not applicable for this building type

Given the above relationships, fragility curves for the complete damage state can be calculated from RVS Final Scores, using the HAZUS (FEMA, 2006) value of 0.64 for beta (the lognormal dispersion parameter in the fragility curve). Such fragility curves are used in the technical evaluation of the RVS procedure in the following section.

2.0 Technical Evaluation of Rapid Visual Screening Procedures

The technical assumptions, data, and mathematical calculations included in the RVS procedure have been recently reviewed (Wang and Goettel, 2006). The conclusions drawn from this evaluation include:

1) The use of seismicity regions, rather than site-specific seismic hazard data, for the RVS procedure substantially reduces the accuracy of RVS results. 2) In some cases, the combinations of RVS Score Modifiers result in Final Scores which are mathematically out of bounds: the Final Scores correspond to probabilities of reaching the complete damage state or probabilities of collapse which exceed one. 3) The RVS Score Modifiers for Soil Types C, D, and E appear to overcorrect for soil effects in comparison to the soil factors in the International Building Code 2003 (International Code Council, 2002).

4) The logarithmic relationship between Final Scores and the probability of collapse at the maximum considered earthquake (MCE) makes results somewhat difficult to interpret, especially for less technical users.

The technical details of the above four aspects of the RVS procedure are reviewed below. The intent of this analysis is not to criticize the RVS procedure, but rather to understand the limitations of the existing RVS procedure in order to make enhancements to the RVS procedure to provide more accurate results for prioritizing seismic retrofits within Oregon.

2.1 RVS Seismicity Regions

The RVS methodology defines three seismicity regions, as shown in Table 3 below. As shown by the following analysis, use of these seismicity regions substantially reduces the accuracy of RVS results, compared to results using USGS seismic hazard data by latitude and longitude.

Table 3 RVS Seismicity Bins

Spectral Region	**Acceleration Response[1] S_s Short Period (0.2 sec)**	**S_l Long Period (1.0 sec)**	**Corresponding PGA Values[2,3]**
Low	<0.167 g	<0.067 g	<0.067 g
Moderate	0.167 g to 0.500 g	0.067 g to 0.200 g	0.067g to 0.200 g
High	>0.500 g	>0.200 g	0.200 g to 1.600 g

[1] in horizontal direction [2] PGA values calculated as S_s divided by a factor of 2.5. [3] maximum PGA value for high seismicity region calculated using the maximum S_s value in FEMA 155 Figure 6-3.

The RVS procedure uses separate evaluation forms for Basic Structural Hazard Score and Score Modifiers for the three seismicity regions defined above. These seismicity regions are in bins defined by 2/3rds of the spectral acceleration values with a 2% chance of exceedance in 50 years. The data source for these data is FEMA 310 (FEMA, 1998).

In the RVS procedure, the seismicity region for a given location can be determined in two ways:

1) By reference to seismicity maps by county, or

2) From USGS seismic hazard data for specific locations by zip code or latitude/longitude.

2.1.1 RVS Seismicity Regions by County

The RVS county seismicity region classification is based on the highest seismicity location in each county. Twenty-two counties in western and southern Oregon are in the high seismicity region, while 14 counties in north-central and north-eastern Oregon are in the moderate seismicity region. The RVS seismicity region classification for Oregon counties is as shown below in Table 4.

Table 4 Oregon Counties by Seismicity Region

Moderate Seismicity Region

High Seismicity Region Baker Morrow Benton Jackson Marion Crook Sherman Clackamas Josephine Multnomah Deschutes Umatilla Clatsop Klamath Polk

Gilliam Union Columbia Lake Tillamook
Grant Wallowa Coos Lane Washington Hood River Wasco Curry Lincoln Yamhill
Jefferson Wheeler Douglas Linn
Harney Malheur

Using the highest seismicity location in each county to determine the seismicity region for the entire county substantially reduces the accuracy of RVS results, especially in counties with a large variation in level of seismic hazard.

The effect of the variation in level of seismic hazard within a single county is illustrated by the Lane County example shown below in Figure 1 and Table 5. We consider three hypothetical identical buildings with identical RVS scores in eastern, central and western Lane County. Using the RVS procedure, the inferred level of seismic risk would be identical for each building, regardless of location within Lane County. When the variation in local seismic hazard is considered, the inferred level of seismic risk (i.e., calculated probability of collapse) at the local MCE (2/3rds of the 2% in 50 year ground motion) varies by a factor of 8 between eastern and western Lane County.

Figure 1

Variation in Seismic Hazard Level Within Lane County, Oregon

The left part of Figure 1 shows the implicit uniform seismic hazard in Lane County, using the RVS seismicity classification by county. The right part of Figure 1 shows schematic contours of seismic hazard levels, with the seismic hazard decreasing markedly from west to east.

Table 5 Variation in Seismic Hazard and RVS Results Within Lane County, Oregon

Location **A: Florence B: Eugene C: McKenzie**

Bridge Building Type C1 C1 C1 RVS Final Score, S 2.0 2.0 2.0 Probability of Collapse at MCE (0.328 g) 1.0% 1.0% 1.0% Probability of Complete Damage State at MCE 7.7% 7.7% 7.7% Inferred Median PGA for Complete Damage 0.82 g 0.82 g 0.82 g Site Specific MCE 0.41 g 0.26 g 0.21 g Probability of Complete Damage State at Site Specific MCE 14.2% 3.5% 1.8% Probability of Collapse at Site Specific MCE 1.8% 0.5% 0.2% Corresponding S value (yields calculated probability of collapse) 1.7 2.3 2.6

Notes: The median value for the complete damage state was inferred from the probability of the complete damage state at the MCE, corresponding to the RVS Final Score of 2.0, using the standard HAZUS (FEMA, 2006) beta value of 0.64. Then, the probability of complete damage at the local MCE was calculated from this fragility curve and the site specific MCE. Finally, the corresponding S value which yields the calculated probability of collapse was calculated, using the RVS definition of Final Score, S, as shown above in Section 1.3.

The variation in RVS results within Lane County is rather dramatic, a factor of 8 in the calculated probability of collapse, even though the level of seismic hazard (local MCE) varies by only a factor of two between Florence and McKenzie Bridge, in western and eastern Lane County, respectively.

The variation in local seismic hazard shown above for Lane County is only about one-quarter of the total variation in local seismic hazard within the RVS high seismicity region, as discussed in the following section. Thus, the above dispersion in RVS results for Lane County reflects only about one-quarter of the total dispersion within the high seismicity region.

2.1.2 RVS Seismicity Region Classification by Latitude and Longitude or Zip Code

FEMA 154 (FEMA, 2002a) notes that the second suggested method, based on USGS seismic hazard data for specific locations by zip code or latitude/longitude is preferred as it allows the user to determine the RVS seismicity region based on a more precisely specified location. Using this method requires the user to go to the USGS website (http://eqhazmaps.usgs.gov/) and to select Hazard by Zip Code or Hazard by Lat/Long (USGS, 2002). Then, entry of appropriate values for the zip code or latitude and longitude returns corresponding local seismic hazard data. The returned seismic hazard data include values for peak ground accelerations (PGA), spectral accelerations (SA) (0.2 second) and SA (1.0 second) for 2%, 5% and 10% probability of exceedance in 50 years.

To determine the appropriate RVS seismicity region for a specified location, the 0.2 and 1.0 second SA values with 2% exceedance probability in 50 years are multiplied by 2/3 and then compared to the bin ranges in Table 1 above. These probabilistic SA values (including the 2/3 multiplier) correspond to the ground motions specified for detailed building seismic evaluations in FEMA 310 “Handbook for the Seismic Evaluation of Buildings – A Prestandard” (FEMA, 1998) and ASCE 31-03 “Seismic Evaluation of Existing Buildings “(ASCE, 2003).

Determining a RVS seismicity region using data for a specified location is an improvement over the method of assigning seismicity region for an entire county based on the highest seismic hazard for the county. However, selecting an appropriate seismicity region does not correct the inaccuracies which arise from the wide variation in seismic hazard levels within a given seismicity region.

As shown in Table 3 above, seismic hazard levels within the moderate and high seismicity regions vary by factors of three and eight, respectively. These very broad ranges of seismic hazard levels within a seismicity region have substantial effects on RVS results – even larger than those discussed above for the variation in seismic hazard level within Lane County.

The effects of variation in seismic hazard level within a seismicity region (moderate and high) are evaluated by the following examples which consider identical buildings with local MCEs (2/3ds of the 2% in 50 year ground motions) equal to the low, median, and high values for RVS moderate and high seismicity regions. Median PGA values for the moderate and high seismicity regions are 0.104 g and 0.328 g, respectively. These median values were taken from the median S_s values for the seismicity regions (FEMA 155, Table 6.3 (FEMA, 2002b)), with PGA values calculated as the S_s values divided by a factor of 2.5. The results of these sample calculations are shown below in Tables 6 and 7.

Table 6 Variation in RVS with Seismic Hazard Level within the High Seismicity Region

Low PGA Median PGA High PGA Building Type C1 C1 C1 RVS Final Score, S 2.0 2.0 2.0 Probability of Collapse at MCE (0.328 g) 1.0% 1.0% 1.0% Probability of Complete Damage State) at MCE 7.7% 7.7% 7.7% Median PGA for Complete Damage[1] 0.82 g 0.82 g 0.82 g Site Specific MCE (2/3rds of 2% in 50 year value) 0.20 0.33 1.60 Probability of Complete Damage State at Site Specific MCE 1.4% 7.7% 85.3% Probability of Collapse at Site Specific MCE 0.2% 1.0% 11.1% Corresponding S value (yields calculated probability of collapse) 2.7 2.0 1.0

[1] This median PGA for the complete damage state and the HAZUS beta value of 0.64 yield a probability of collapse at 0.33 g (the median PGA level for the High Seismicity Region) of 1%, which matches the results of an RVS Final Score of 2.0.

Variation in MCE within the Data or Result

High Seismicity Region **Table 7 Variation in RVS with Seismic Hazard Level within the Moderate Seismicity Region**

Low PGA Median PGA High PGA Building Type C1 C1 C1 RVS Final Score, S 2.0 2.0 2.0 Probability of Collapse at MCE (0.328 g) 1.0% 1.0% 1.0% Probability of Complete Damage State) at MCE 7.7% 7.7% 7.7% Median PGA for Complete Damage[1] 0.26 g 0.26 g 0.26 g Site Specific MCE (2/3rds of 2% in 50 year value) 0.07 0.10 0.20 Probability of Complete Damage State at **Site Specific** MCE 1.7% 7.7% 34.3% Probability of Collapse at **Site Specific** MCE 0.2% 1.0% 4.5% Corresponding S value (yields calculated probability of collapse) 2.6 2.0 1.4

[1] This median PGA for the complete damage state and the HAZUS beta value of 0.64 yield a probability of collapse at 0.10 g (the median PGA level for the Moderate Seismicity Region) of 1%, which matches the results of an RVS Final Score of 2.0.

Variation in MCE within the Data or Result

Moderate Seismicity Region

The above tables demonstrate that example buildings having fragility curves with median PGA values for the complete damage state of 0.82 g (high seismicity region) and 0.26 g (moderate seismicity region) with HAZUS (FEMA, 2006) betas of 0.64 yield calculated probabilities of collapse of 1% at the median PGA value for each seismicity region. These results match the RVS results at the median PGA for each seismicity region.

The above calculations show a wide variation in calculated probabilities of collapse at the low and high PGA values for the seismicity regions. For the high seismicity region, the calculated probabilities of collapse vary by a factor of about 60 between sites at the low and high end of the range of seismic hazard level within the high seismicity region. For the moderate seismicity region, the calculated probabilities of collapse vary by a factor of about 20 between sites at the low and high end of seismic hazard level within the moderate seismicity region. In the RVS procedure, the inferred level of risk for the above sample buildings in each seismicity region would be identical, with no consideration of the variation in level of seismic hazard within each seismicity region. The above example calculations demonstrate that the actual level of risk varies by large factors (about 60 and about 20 in above examples) and thus that the RVS results are substantially limited in accuracy. For other buildings with different fragility curves, the factors by which the actual level of risk differs over the range of seismic hazard levels will vary.

To the extent that RVS scores are used to evaluate populations of buildings and to prioritize detailed evaluations and seismic retrofits, these limitations of the existing RVS procedure will result in substantially less than optimum allocation of mitigation funds and risk reduction actions. Use of RVS results will tend to result in too many retrofits in lower hazard areas and too few retrofits in higher hazard areas, within a given RVS seismicity region.,

Fortunately, this substantial deficiency in the existing RVS procedure can be corrected by calculating RVS results using site-specific seismic hazard data, rather than calculating RVS results by seismicity region. An enhanced RVS method, which includes this modification, is discussed in Section 3 of this report.

2.2 RVS Final Scores

As discussed in Section 1.3, RVS Final Scores are explicitly the probability of collapse, given the MCE, as defined by the RVS methodology:

$\text{BSH} = -\log_{10}$ [P (collapse given MCE)]. (FEMA 155, Equation 6-1, FEMA, 2002b)

Given that the probability of collapse cannot exceed 1.0 (100% probability of collapse), then the minimum RVS Final Score which is physically meaningful is zero. As shown in Table 8 below, there are many combinations of RVS Score modifiers which result in RVS Final Scores below 0.0. For the 45 combinations of building type and seismicity region used in RVS, there are 30 possible combinations which can have Final Scores below 0.0. Such scores are not physically meaningful.

In the RVS methodology, the probabilities of collapse are calculated in a two step process: 1) the probability of the complete damage state is calculated and then 2) the probability of collapse if the complete damage is reached is estimated from the HAZUS (FEMA, 2006) relationship. The probability of collapse if the complete damage state is reached ranges from 0.03 to 0.15 for various building types and combinations of low-, mid- and high-rise buildings (cf. Table 2 in Section 1.3). A

more rigorous bound on physically meaningful RVS Final Scores is that the probability of the complete damage state cannot exceed 1.0 (100% probability). Thus, physically meaningful RVS Final Scores cannot be lower than the values shown below in Table 9.

Table 8 RVS Basic Structural Hazard Scores and Minimum Possible Final Scores

Building Type	Low Seismicity Region			Moderate Seismicity Region			High Seismicity Region		
	BSH	Min SM	Min S	BSH	Min SM	Min S	BSH	Min SM	Min S
W1	7.4	-6.6	0.8	5.2	-5.2	0.0	4.4	-3.0	1.4
W2	6.0	-5.8	0.2	4.8	-5.5	-0.7	3.8	-4.3	-0.5
S1	4.6	-4.8	-0.2	3.6	-4.5	-0.9	2.8	-3.7	-0.9
S2	4.8	-4.8	0.0	3.6	-4.5	-0.9	3.0	-4.0	-1.0
S3	4.6	-2.8	1.8	3.8	-2.5	1.3	3.2	-2.1	1.1
S4	4.8	-5.0	-0.2	3.6	-4.5	-0.9	2.8	-3.5	-0.7
S5	5.0	-5.0	0.0	3.6	-4.3	-0.7	2.0	-2.5	-0.5
C1	4.4	-4.3	0.1	3.0	-5.1	-2.1	2.5	-4.4	-1.9
C2	4.8	-5.0	-0.2	3.6	-4.5	-0.9	2.8	-3.3	-0.5
C3	4.4	-5.2	-0.8	3.2	-5.1	-1.9	1.6	-2.5	-0.9
PC1	4.4	-2.6	1.8	3.2	-2.3	0.9	2.6	-1.7	0.9
PC2	4.6	-4.5	0.1	3.2	-4.0	-0.8	2.4	-3.5	-1.1
RM1	4.8	-4.6	0.2	3.6	-4.5	-0.9	2.8	-2.9	-0.1
RM2	4.6	-4.1	0.5	3.4	-4.0	-0.6	2.8	-2.9	-0.1
URM	4.6	-4.3	0.3	3.4	-4.4	-1.0	1.8	-2.5	-0.7

BSH is the RVS Basic Structural Hazard Score. Min SM is the lowest possible combination of Score Modifiers. Min S is the minimum possible RVS Final Score.

Table 9 Minimum Credible RVS Final Scores[1]

Building Type	Minimum Credible Final Score		
	Low-Rise	Mid-Rise	High-Rise
W1	1.52	NA	NA
W2	1.52	NA	NA
S1	1.10	1.30	1.52
S2	1.10	1.30	1.52
S3	1.52	NA	NA
S4	1.10	1.30	1.52
S5	1.10	1.30	1.52
C1	0.89	1.00	1.30
C2	0.89	1.00	1.30
C3	0.82	0.89	1.00
PC1	0.82	NA	NA
PC2	0.82	0.89	1.00
RM1	0.89	1.00	NA
RM2	0.89	1.00	1.30
URM	0.82	0.82	NA

NA: not applicable for this building type

[1] Probability of complete damage state is 1.0

Comparison of Tables 8 and 9 indicates that for nearly all possible combinations of RVS building types and seismicity regions, the lowest possible RVS Final Score is lower than the physically meaningful limit (probability of complete damage state = 1.0).

Possible explanations for the problematic RVS Final Scores discussed above include:

1) The individual score modifiers are very large in many cases, and

2) The Basic Structural Hazard Score (BSH) and the Score Modifiers (SMs) are combined linearly to obtain the Final Score (S).

The following examples are provided to help illustrate some of the apparent difficulties with the present RVS Score Modifiers.

1) Score Modifiers for "vertical irregularity" range from -1.0 to -4.0, for various building types and seismicity regions. These Score Modifiers correspond to increases in the probability of collapse at the MCE by factors ranging from 10 to 10,000. These very large increases may or may not be reasonable for major structural irregularities such as a markedly soft first story, but are almost certainly not reasonable for minor or trivial vertical irregularities.

2) Score Modifiers for "plan irregularity" are -0.8 for the low seismicity region and -0.5 for the moderate and high seismicity regions for all building types. These Score Modifiers correspond to increases in the probability of collapse at the MCE by factors of 6.31 and 3.16 for the low, and moderate-high seismicity regions, respectively. These substantial increases may be reasonable for major structural irregularities such as very irregular plans with pronounced re-entrant shapes, but are almost certainly not reasonable for minor or trivial plan irregularities.

3) To illustrate the complications arising from simple linear combination of Score Modifiers, we consider a C1 building in the moderate seismicity region. Possible Score Modifiers are shown in Table 10 below. Selection of these Score Modifiers individually corresponds to increasing the probability of collapse at the MCE by factors ranging from 3.16 to 100. In combination, selection of all four Modifiers increases the corresponding probability of collapse by a factor of more than 125,000.

Table 10 Linear Combination of Score Modifiers: C1 Building in Moderate Seismicity Region

Score Modifier Multiplicative Modifier SM

Factor Vertical irregularity -2.0 100 Plan irregularity -0.5 3.16 Pre-code -1.0 10 Soil Type E -1.6 39.81 Total -5.1 125,893

The above example is dramatic, but is not the most extreme possible example. Some possible combinations of Score Modifiers correspond to increases in the probability of collapse at the MCE by factors of more than 10^6.

Mathematically, there are many alternative ways to combine Score Modifiers that would be more sophisticated than the simple linear combination used in RVS. For example, Score Modifiers could be applied by root mean square. Or, the first Score Modifier could be applied to the BSH, then the mathematical impact of subsequent Score Modifiers could be systematically adjusted in proportion to the magnitude of the adjustments already made by previous Score Modifiers. Furthermore, more detailed engineering judgment could be applied to determine the most likely governing Modifiers for each structural building type, when more than one Modifier is selected. Such possible enhancements to the RVS methodology are beyond the present effort: such enhancements would require a detailed upgrade of the existing RVS methodology (See Section 5.2 for further comments on possible enhancements to RVS).

At first glance, it might appear that the above mathematical irregularities in RVS Final Scores and Score Modifiers might not substantially affect the intended use of RVS, which is to identify a subset of the screened buildings with Final Scores below a user-defined cut-off Score (often 2.0) that are then subjected to further study. The out-of-bounds Final Scores are all below 2.0.

The apparent irregularities in RVS Score Modifiers and Final Scores will also affect the relative risk (i.e., Final Score) assigned to various buildings and also strongly affect which buildings are deemed above or below any defined cut-off score. These irregularities are significant and the above results suggest that a thorough review and updating of the Score Modifiers and the mathematical way in which individual Score Modifiers are combined may be warranted to improve the accuracy and meaningfulness of RVS results. This future improvement in the RVS methodology is addressed further in

Section 5.2.

2.3 RVS Soil Factors

The Score Modifiers for Soil Types C, D, and E are among the largest Score Modifiers in the RVS method. These Score Modifiers for soil type have a large influence on the Final Score, S, on the overall interpretation of RVS results, thus on any risk reduction priorities based on RVS results. Because of the importance of the Score Modifiers for soil types, we evaluate these modifiers quantitatively and compare them to the IBC 2003 (International Code Council, 2002) soil factors.

2.3.1 RVS Soil Rock Factors

RVS Final Scores include Score Modifiers for soil types C, D and E. These Score Modifiers for the 15 building types are shown below in Table 11 for the moderate and high seismicity regions.

Table 11 RVS Score Modifiers for Soil Types C, D, and E[1]

Seismicity Region	Soil Type	W1	W2	S1	S2	S3	S4	S5	C1	C2	C3	PC1	PC2	RM1	RM2	URM
High	C	0.0	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
High	D	0.0	0.8	0.6	0.6	0.6	0.6	0.4	0.6	0.6	0.4	0.6	0.6	0.6	0.6	0.6
High	E	0.0	0.8	1.2	1.2	1.0	1.2	0.8	1.2	0.8	0.8	0.4	1.2	0.4	0.6	0.8
Moderate	C	0.2	0.8	0.6	0.8	0.6	0.8	0.8	0.6	0.8	0.6	0.6	0.6	0.8	0.6	0.4
Moderate	D	0.6	1.2	1.0	1.2	1.0	1.2	1.2	1.0	1.2	1.0	1.0	1.2	1.2	1.2	0.8
Moderate	E	1.2	1.8	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6

[1] Excerpted from the RVS Data Collection Forms (FEMA 154 (FEMA, 2002a), Appendix B, pages 79-80).

As per the RVS methodology, these Score Modifiers are directly related to the probability of collapse at the MCE (maximum considered earthquake) via the RVS relationship presented in Section 1.3:

Final Score $S = -\log_{10} P$ (collapse given the MCE).

These Score Modifiers for soil types C, D, and E correspond to the multiplicative factors for the increase in the probability of collapse given the MCE shown below in Table 12. As noted above, these factors also apply to the probability of being in the complete damage state, which is linked to the probability of collapse in RVS by the HAZUS (FEMA, 2006) relationship shown in Table 2.

Table 12 Increase in P (collapse) for Score Modifiers for Soil Types

RVS Soil Modifier	Multiplicative Factor[1]
-1.80	63
-1.60	40
-1.20	16
-1.00	10
-0.80	6
-0.60	4
-0.40	2.5
-0.20	1.6

[1] Increase in P (collapse) which is also equal to the increase in P (complete damage) via the HAZUS (FEMA, 2006) fragility curve relationships.

As shown above, the RVS Score modifiers for soils correspond to large increases in the probability of collapse at the MCE, with score modifiers of -1.0 or larger corresponding to increases in P (collapse) by a factor of 10 or more.

These RVS soil factors differ both conceptually and mathematically from the soil factors in the 2003 IBC (International Code Council, 2002)

First, the RVS (FEMA, 2002a) soil factors are constant for a given building type and seismicity region: the values do not vary with the level of ground motion. This is an important difference, because the 2003 IBC values vary markedly with the level of ground motion. For example, at high levels of ground motion, the IBC factors are 1.0 (no amplification) for soil types C and D and 0.9 (deamplification) for soil type E. In contrast, the RVS Score Modifiers for these soil types correspond to large increases in risk (probability of collapse) for these soil types.

Second, the magnitudes of the RVS soil-rock factors appear large in absolute terms as illustrated by the inferred multiplicative factors for the complete damage state as shown above.

2.3.2 IBC 2003 Soil Rock Factors

The IBC soil-rock factors are shown below in Table 13 (Table 1615.1.2(1) in IBC (2003). These factors represent the ratios in ground motions for various types of rock and soil, compared to Site Class B (soft rock).

Table 13 IBC Soil-Rock Factors

Site Mapped Spectral Response Acceleration at Short Periods Class

$S_s < 0.25$ $S_s = 0.50$ $S_s = 0.75$ $S_s = 1.00$ $S_s > 1.25$ A 0.8 0.8 0.8 0.9 0.8 B 1.0 1.0 1.0 1.1 1.0 C 1.2 1.2 1.1 1.0 1.0 D 1.6 1.4 1.2 1.1 1.0 E 2.5 1.7 1.2 0.9 0.9 F Note b Note b Note b Note b Note b

a. Use straight-line interpolation for intermediate values of mapped spectral acceleration at short period S_s. b. Site-specific geotechnical investigation and dynamic site response analyses shall be performed to determine appropriate values, except that for structures with periods of vibration equal to or less than 0.5 second, values of F_a for liquefiable soils are permitted to be taken equal to the values for the site class determined without regard to liquefaction in Section 1615.1.5.1.Table 1615.1.2(1)

Mapped Values Spectral of Site Response Coefficient Acceleration F_a as a Function at Short of Site Periods

Class

$(S_s)^a$

For the present purposes, approximate soil-rock factors for ground motions expressed in terms of PGA may be inferred from the above table of short period (S_s) spectral acceleration values by dividing the S_s values by 2.5. For example, a value for S_s of 1.00 g corresponds to a PGA of about 0.40 g and so on.

2.3.3 Comparison of RVS and IBC 2003 Soil Factors

RVS results that illustrate the effects of the soil factors are shown below in Table 14. RVS results were calculated for two low-rise building types: C1 and URM. These results, as are all RVS results, are calculated at the median values of seismic hazard for each seismicity region: 0.104 g and 0.328 g, for the moderate and high seismicity regions, respectively.

There is a strong variation in the probability of collapse as a function of soil type. For RVS Final Scores of 2.0 and rock type B, the probability of collapse is 1% for both the moderate and high seismicity regions (i.e., per the mathematical definition of RVS Final Score, S). The calculated probability of collapse increases markedly with the progression from soil types C, D, and E. For soil type E, probability of collapse) values are up about 15 times higher and 40 times higher, for the high and moderate seismicity regions, respectively. These substantial increases in P probability of collapse arise because of the large Score Modifiers for soil type E.

Table 14 Sample Results for RVS Method

Seismicity Region	Soil	RVS Soil Factors		RVS Final Score[1]		P (collapse)[2]	
		C1	URM	C1	URM	C1	URM
High	B	0.0	0.0	2.0	2.0	1.00%	1.00%
High	C	0.4	0.4	1.6	1.6	2.51%	2.51%
High	D	0.6	0.6	1.4	1.4	3.98%	3.98%
High	E	1.2	0.8	0.8	1.2	15.85%	6.31%
Moderate	B	0.0	0.0	2.0	2.0	1.00%	1.00%
Moderate	C	0.6	0.4	1.4	1.6	3.98%	2.51%
Moderate	D	1.0	0.8	1.0	1.2	10.00%	6.31%
Moderate	E	1.6	1.6	0.4	0.4	39.81%	39.81%

[1] assuming a Final Score of 2.0 before score modifier for soil type. [2] in RVS, the level of ground shaking is determined only by the seismicity region and does not vary with local seismic hazard within a given seismicity region.

We compare IBC-based soil factors with the above RVS soil factors by first obtaining the appropriate IBC soil factors for the 0.104 g and 0.328 g median PGA values for the moderate and high seismicity regions, respectively. As per the guidance in footnote "a" in Table 13, the IBC soil factors were interpolated linearly for accelerations between the tabulated values. Then, the IBC short period spectral acceleration (S_s) values are converted to PGA values by dividing the S_s spectral accelerations by a factor of 2.5. These values are shown below in Table 15.

Table 15 IBC Soil Factors: Interpolated and Converted to PGA

Ground Motion (g)		IBC (2003) Soil-Rock Factors[1]			
IBC S_s	PGA	Rock B	Soil C	Soil D	Soil E
<0.25	0.1	1.000	1.200	1.600	2.500
0.260	0.104	1.000	1.200	1.592	2.468
0.50	0.2	1.000	1.200	1.400	1.700
0.75	0.3	1.000	1.100	1.200	1.200
0.820	0.328	1.000	1.072	1.172	1.116
1.00	0.4	1.000	1.000	1.100	0.900
>1.25	0.5	1.000	1.000	1.000	0.900

[1] Shaded values for PGAs of 0.10 and 0.33 soil factors are by linear interpolation as per IBC (2003)

IBC-based results were obtained by selecting fragility curves to match RVS results exactly for Soil Type B (a probability of collapse of 1% at the median PGA for each seismicity region. For a C1 (concrete moment frame) building, these values are 0.82 g and 0.26 g, for the high and moderate seismicity regions, respectively. For

a URM (unreinforced masonry) building, these values are 0.86 g and 0.27 g, respectively. Both fragility curves use the HAZUS (FEMA, 2006) beta value of 0.64 and the HAZUS relationship between the probability of the complete damage state and the probability of collapse.

These results are summarized in Table 16 below.

Table 16 Calculated Probabilities of Collapse using Fragility Curves and IBC Soil Factors

Seismicity Region	Soil	IBC Factor	PGA	P (collapse)[1] C1	URM
High	B	1.000	0.328	1.00%	1.00%
High	C	1.072	0.352	1.22%	1.23%
High	D	1.172	0.384	1.55%	1.57%
High	E	1.116	0.366	1.36%	1.37%
Moderate	B	1.000	0.104	1.00%	1.00%
Moderate	C	1.200	0.125	1.65%	1.68%
Moderate	D	1.592	0.166	3.15%	3.28%
Moderate	E	2.468	0.257	6.43%	6.96%

[1] Calculations for buildings with median PGA values for the complete damage state which yield a 1% probability of collapse at the median PGA for each seismicity region, for Soil Type B. For C1 building, these values are 0.818 g and 0.259 g for the high and moderate seismicity regions, respectively. For the URM building, these values are 0.858 g and 0.272 g, respectively.

Then, probabilities of collapse for Soil Types C, D, and E are calculated using the above fragility curves and the higher PGA values for each soil type, from the IBC soil factors shown above in Table 15.

The RVS and IBC-based results are compared directly in Table 17 below which shows the ratio of calculated probabilities of collapse (relative to Soil Type B) between the RVS results (Table 15 above) and the IBC-based results (Table 16 above). The RVS results show increases in the probability of collapse, compared to those calculated using the IBC-soil factors directly factors of about 1.5 to 3 for Soil Types C and D and factors of about 5 to 12 for Soil Type E.

Table 17 Comparison of RVS and IBC-Based Results: Ratio of the Probability of Collapse Calculated Using the RVS Soil Score Modifiers vs. Using the IBC Soil Factors

Seismicity Region	Soil	Ratio: (RVS/IBC) C1	URM
High	B	1.0	1.0
High	C	2.1	2.1
High	D	2.6	2.5
High	E	11.7	4.6
Moderate	B	1.0	1.0
Moderate	C	2.4	1.5
Moderate	D	3.2	1.9
Moderate	E	6.2	5.7

The above results suggest that the existing RVS procedure may significantly overestimate the effects of Soil Types C and D, and especially Soil Type E. The

differences between RVS results and IBC-based results arise because:
1) RVS soil factors are large, and
2) RVS soil factors, unlike the IBC soil factors, are constant and do not vary with level of ground shaking within a seismicity region.

The apparent overcorrection of results for soil types in the RVS procedure may result in incorrect sorting of buildings above or below cut-off Final Score values and thus may result in less than optimum allocation of mitigation funds and risk reduction actions which are based on RVS results.

2.4 Logarithmic Scale for the RVS Final Score

The RVS Final Score, S, is logarithmically related to the probability of collapse at the RVS-defined Maximum Considered Earthquake (MCE) for a given seismicity region as discussed in Section 1.3:

$$S = -\log_{10} [P \text{ (collapse given MCE)}].$$

From discussions with the Oregon University System (OUS) users of the RVS methodology, we conclude that the use of a logarithmic scale substantially confuses many users (especially less technical users) and unnecessarily obfuscates the meaning of RVS results (i.e., Final Scores). It is unclear to many users that a building with a Final Score of 2.5 has an inferred factor of ten higher probability of collapse than a building with a Final Score of 1.5.

It is also difficult for many users to interpret differences between Final Scores, which appear to be minor, but which represent substantially different levels of risk.

For example, Final Scores of 1.9 and 2.3 represent a factor of four difference in probability of collapse. There is also a more subjective impediment to using RVS Final Scores to motivate mitigation actions – lower Final Scores correspond to higher levels of seismic risk.

We note that a RVS Score of, for example, 1.3 doesn’t have the same public policy impact as stating the mathematically equivalent information that the building has an estimated 5% chance of collapse and an estimated 50% chance of being a complete economic loss (i.e., in the complete damage state) at a level of ground shaking corresponding to that currently used for the design of new buildings.

Finally, we conclude that scores ranging from zero to 100 are easier for some to understand and use than the traditional RVS scores. As an example, OUS creates a needs matrix with scores that range from zero to 100 for both deferred maintenance needs and energy efficiency needs. Scores that reflect preliminary seismic risk that range from 0 to 100 are easier to integrate into the existing OUS needs matrix than traditional RVS scores.

2.5 Conclusions: Technical Review of RVS Methodology

The preceding technical review of the RVS methodology draws the authors to the following major conclusions:

1) The use of seismicity regions, rather than site-specific seismic hazard data, for the RVS procedure substantially reduces the accuracy of RVS results. This conclusion holds for either of the two RVS seismic hazard methods (using the seismicity region maps by county or determining the seismicity region from site-specific data). The variation in probability of collapse at a site-specific Maximum Considered Earthquake varies by at least a factor of 8 within a single county and by factors of at least 20 to 60 for the moderate and high seismicity regions overall; none of this variation is considered by the existing RVS methodology.
2) In some cases, the combinations of RVS Score Modifiers result in Final Scores which are mathematically out of bounds: the Final Scores correspond to probabilities of reaching the complete damage state or probabilities of collapse which exceed one. These irregularities in Score Modifiers affect the relative risk assigned to various buildings (i.e., the Final Score) and also affect which buildings are deemed to be above or below any defined cut-off score and thus directly affect the buildings for which additional study is recommended.
3) The RVS Score Modifiers for Soil Types C, D, and E appear to substantially overcorrect for soil effects in comparison to the soil factors in the 2003 IBC (International Code Council, 2002).

4) The logarithmic relationship between Final Scores and the probability of collapse at the maximum considered earthquake (MCE) makes results somewhat difficult to interpret and apply.

In combination, the above limitations of the existing RVS methodology, reduce the accuracy and usefulness of RVS results.

3.0 DOGAMI Enhancements to RVS: E-RVS

The previous section outlined several technical aspects of the current RVS methodology where enhancements would substantially improve the accuracy and usefulness of RVS results, including:

- Improve the accuracy of seismic hazard data by using site-specific MCEs rather than median MCEs for broad seismicity regions,
- Reduce the effects of out of bounds RVS Final Scores, by avoiding interpretation of RVS Final Scores which are not physically meaningful (i.e., the Final Score must correspond to the probability of the complete damage state < 1.0),
- Adjust the RVS soil-rock Score Modifiers to yield results which are consistent with the NEHRP/IBC soil factors.
- Make results easier to understand and apply by using linear rather than logarithmic scales for results.

The above enhancements are incorporated into DOGAMI's enhanced RVS methodology, or E-RVS. Scores for CODA (Complete Damage) and LSRI (Life Safety Risk Index) are produced.

3.1 Oregon Seismic Hazard Calculator

3.1.1 Use Site Specific Seismic Hazard Data (Local MCE)

An important enhancement to the existing RVS methodology is to calculate the Final Score, S, or equivalently the probability of collapse, at the local Maximum Considered Earthquake (MCE), rather than at the median MCE for seismicity regions which encompass a wide range of seismic hazard levels. This enhancement removes the large dispersion in the meaning of identical RVS scores because of the large variation in local MCE within some counties and the even larger variation in local MCE within the RVS-defined seismicity regions.

The existing RVS methodology suggests two methods for determining seismicity region: 1) using the county maps in FEMA 154 (FEMA, 2002a) or 2) using site specific USGS data to determine the appropriate seismicity region. Neither of

these two methods corrects the large dispersion of seismic hazard levels within a county or within a RVS-defined seismicity region.

RVS Final Scores explicitly define the probability of collapse at a defined level of ground shaking (the median value for each seismicity region). The probability of collapse is in turn directly related to the probability of being in the complete damage state via the HAZUS (FEMA, 2006) relationship between the complete damage state and the probability of collapse (cf. Table 2 in Section 1.3).

The mathematical steps to calculate the enhanced RVS (E-RVS) adjusted Final Score, S) are summarized below.

1) Conduct RVS evaluation and obtain the Final Score, S. 2) Determine the probability of being in the complete damage state at the median MCE level of ground shaking for the appropriate RVS seismicity region from the probability of collapse (Final Score) and the probability of collapse if the complete damage state is reached (cf. Table 2). 3) Infer a fragility curve (the median ground motion for the complete damage state) from the above probability at the RVS median level of ground shaking, using the HAZUS (FEMA, 2006) beta (lognormal dispersion parameter) value of 0.64. 4) From the fragility curve for the complete damage state, calculate the probability of the complete damage state, the probability of collapse, and the equivalent adjusted Final Score, S, for the local MCE.

The above calculations are done automatically in the DOGAMI E-RVS software which requires only that the user enter the RVS score, building type, seismicity region, soil-rock type (all of which are part of the existing RVS procedure) and the local MCE (2/3rds of the 2% in 50 year ground motion value). The E-RVS software uses peak ground acceleration (PGA) for these calculations.

To facilitate users obtaining the correct local seismic hazard data, we have also developed an Oregon Seismic Hazard Calculator, which returns the necessary seismic hazard data (e.g., a full seismic hazard curve) upon entry of a site's latitude and longitude and soil-rock type. The Oregon Seismic Hazard Calculator uses the consensus USGS national seismic hazard data (gridded values) and automatically looks up and interpolates between the four surrounding grid points to obtain the site seismic hazard data necessary for the above calculation. An example printout from the Oregon Seismic Hazard Calculator is shown below in Figure 2.

Figure 2 Example Printout from the Oregon Seismic Hazard Calculator

Seismic Hazard Data by Latitude - Longitude OREGON

Version 1.01 February 20, 2007
Project Name: Deep Creek Bridge
Date:
February 20, 2007 Address: Clackamas County
User Name:
A. B. User City, State, Zip:
Enter Site Latitude-Longitude
Degrees Minutes Seconds in degrees-minutes-seconds
45 23 27.23 OR in decimal degrees
Longitude:
122 23 26.09 122.390581 Enter Project Site Soil/Rock Type:
D Soil/Rock entries must match letter codes exactly.
Soil Rock Choices:
Rock

AB Soil/Rock types and definitions as per IBC 2003 (2006). Very Dense Soil CFirm Soil D If soil/rock unknown, use Firm Soil D as default. Soft Soil EVery Soft Soil

F Site specific geotechnical analysis encouraged for Soil F
PGA Annual P

Seismic Hazard Curve 0.008800 1.145E-01 0.012320 1.005E-01 0.017248 8.391E-02 0.024112 6.587E-02 0.033792 4.825E-02 0.047344 3.322E-02 0.066176 2.188E-02 0.092752 1.387E-02 0.129888 8.514E-03 0.180600 5.028E-03 0.240845 2.750E-03 0.311280 1.399E-03 0.367382 6.426E-04 0.437891 2.583E-04 0.556000 8.588E-05 0.778000 2.260E-05 1.090000 4.449E-06
0.000001 1.520000 6.103E-07 2.130000 3.300E-08
2/3rds of 2% in 50 year PGA value: 0.269 Enter this value into the E-RVS spreadsheet
Reference PGA values: g % g
10% in 50 years: 0.269 26.9% PGA values are shown as fractions of g, the acceleration of gravity. 5% in 50 years: 0.334 33.4% Thus, for example, 0.500 means 0.5 g or 50% of g. 2% in 50 years: 0.403 40.3%
Decimal Calculated Latitude:
45.390897
Site Hazard Data
0.10.01

) ecnadeecxE(Pl aunn $_{A}$ 0.001 0.0001

0.00001

0.00 0.20 0.40 0.60 0.80 1.00 1.20 1.40 1.60 PGA (g)

3.1.2 Soil-Rock Factors

The Oregon Seismic Hazard Calculator, starts with the USGS PGA values for rock sites (actually, for the B/C boundary) and then makes adjustments for soil type and adjustments for earthquake magnitude/duration.

The soil factors used in the Oregon Seismic Hazard Calculator are shown below in Table 18. These factors are interpolated from the 2003 IBC (International Code Council, 2002) factors shown previously in Table 13, simplified by using a factor of 1.000 for Rock Types A and B. This simplification was made because there are essentially no buildings on Type A rock in Oregon.

Table 18 Oregon Seismic Hazard Calculator Soil-Rock Factors

Soil/Rock	Acceleration (PGA, g)										
Type	<0.074	0.103	0.145	0.203	0.284	0.397	0.556	0.778	1.090	1.520	2.130
	Soil/Rock Factors										
AB	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
C	1.200	1.200	1.200	1.197	1.116	1.003	1.000	1.000	1.000	1.000	1.000
D	1.600	1.594	1.510	1.394	1.232	1.103	1.000	1.000	1.000	1.000	1.000
E	2.500	2.476	2.140	1.685	1.280	0.909	0.900	0.900	0.900	0.900	0.900

3.1.3 Magnitude-Duration Adjustments

The DOGAMI E-RVS enhancements to the RVS methodology draw directly on HAZUS (FEMA, 2006) fragility curves and other HAZUS (FEMA, 2006) consensus results such as the relationship between the complete damage state and the probability of collapse for various building types. The HAZUS (FEMA, 2006) fragility curves are derived in substantial part from historical experience with earthquake damage in California, predominantly for earthquakes in the roughly M7+ range.

In Western Oregon, the dominant seismic source is the Cascadia Subduction

Zone where the characteristic earthquakes are very large magnitude events (M8+) with correspondingly very long duration ground shaking. For a given level of shaking, the long duration shaking is expected to result in more damage than would be experienced in much shorter duration earthquakes such as crustal M7 earthquakes in California.

To account for the longer duration shaking expected in Western Oregon, the most rigorous approach would be to develop complete new sets of building fragility curves taking into account not only the duration of shaking but also the spectral content of Cascadia Subduction Zone earthquakes. Such an effort is beyond the scope of our current enhancements to RVS.

To account approximately for the higher levels of damage expected from long duration Cascadia Subduction Zone earthquakes, we adopt the same simplified approach used in the FEMA seismic hazard software for Washington State (FEMA, 2005). Seismic hazard curves are adjusted to increase the expected damage levels as follows:

- For sites with longitudes west of -123 degrees, increase PGA values under 0.30 g by 15% and increase PGA values from 0.30 to 0.40 g by 10%.
- For sites with longitudes east of -123 degrees and west of -122.5 degrees, increase PGA values under 0.30 g by 10 % and increase PGA values from 0.30 to 0.40 g by 5 %.
- For sites east of -122.5 degrees, no adjustments.

Making adjustments by longitude reflects the approximately north-south alignment of the Cascadia Subduction Zone (CSZ), with correspondingly diminishing contributions from the CSZ with increasing distance eastwards from the Oregon coast. We recognize that these empirical adjustments are based largely on professional judgment and that they are approximate only. An alternative approach of using the USGS disaggregated ground motions for each USGS seismic hazard data grid point was beyond the scope of our present effort. Accounting for the effects of long duration shaking approximately is preferable to not considering such effects and we believe that this FEMA method is acceptable for the present purposes, especially given the intrinsically approximate nature of the RVS methodology.

3.2 Oregon E-RVS Calculator

3.2.1 Adjust for Out of Bounds RVS Final Scores

As noted in Section 2.2, there are many possible combinations of RVS Basic Structural Hazard Scores and Score Modifiers which yield Final Scores lower than the physically meaningful limits that neither the probability of collapse nor the probability of the complete damage state can exceed 1.0 (cf. Tables 8 and 9).

In the DOGAMI E-RVS methodology, interpretation of possible out of bounds scores is precluded simply by truncating the maximum possible probability of being in the complete damage state at 99%. This truncation is equivalent to limiting RVS Final Scores to the minimum physically meaningful values shown in Table 9.

3.2.2 Adjust the RVS Score Modifiers for Soil Types C, D, and E.

As documented by the calculations summarized in Section 2.3, the RVS Score Modifiers for Soil Types C, D, and E are larger than the corresponding soil-rock factors in the IBC (2003). As shown in Table 17, the RVS Score Modifiers correspond to increasing the probability of collapse for example buildings by factors from about 2 to nearly 12 in the high seismicity region and by factors of about 1.5 to 6 in the moderate seismicity region, compared to results using the IBC 2003 soil factors. The RVS Score Modifiers for Soil Types C, D, and E may likely overcorrect for soil effects, especially in the high seismicity region.

To avoid this possible overcorrection, the DOGAMI E-RVS methodology removes the Score Modifier component from the RVS Final Score S and, instead, accounts for soil-rock factors in the seismic hazard data, using the IBC 2003 soil factors as documented in Section 2.3.3 above.

3.2.3 Use Linear Rather than Logarithmic Results Scales

As noted in Section 2.4, experience suggests that non-technical users often have difficulty in correctly interpreting RVS Final Scores because they are logarithmic rather than linear. For example, a RVS Final Score of 1.3 doesn't have the same public policy impact as stating the mathematically equivalent information that the building has a 50% chance of being in the complete damage state (i.e., a complete economic loss necessitating replacement rather than repair).

The DOGAMI CODA/LSRI methodology shows the linear equivalent of RVS Final Scores in two ways:

1) CODA, the probability of the complete damage state at the local MCE, and

2) LSRI, Life Safety Risk Index which is 100 times the probability of collapse at the local MCE (i.e., the probability of collapse expressed as a percentage).

The probability of the complete damage state, CODA, is much larger than the probability of collapse (cf. Table 2) and is the best RVS measure of potential economic loss. The probability of collapse, LSRI, is the best RVS measure of life safety risk. Experience in Oregon suggests that these two linear measures of risk are more complete, more understandable and more usable than the RVS Final Score, S, and have the additional advantage of increasing the public policy driving force for implementation of mitigation actions.

4.0 Applications of DOGAMI E-RVS Method

4.1 Example 1: Western Oregon University

The DOGAMI E-RVS methodology was applied in a pilot study for Western Oregon University. An example of the E-RVS results compared with the RVS

results are shown on a campus map (Figure 3). An example printout of the E-RVS summary table developed to facilitate the calculations necessary for this enhancement of the RVS procedure is shown below in Table 19. This example shows the RVS, E-RVS, CODA and LSRI scores and illustrates the modifications made to RVS results at a single geographic location. It includes 19 buildings with RVS scores below 2.5 at Western Oregon University in Monmouth, Oregon. These 19 buildings are a subset of the 46 major buildings on campus. The additional 27 buildings were not included in this example, as they had RVS scores of 2.5 or higher, indicating a low level of probable risk.

The DOGAMI E-RVS methodology, as outlined above, closely follows the logic and mathematics inherent in RVS, along with the mathematics of the HAZUS (FEMA, 2006) fragility curves. The enhancements, especially the determination of the probability of collapse at the local MCE, substantially improve the accuracy and meaningfulness of RVS results. E-RVS results, including the probabilities of being in the complete damage state (CODA) and the probability of collapse (LSRI) are analogous to the RVS Final Score which is also an explicit measure of the probability of collapse and an implicit measure of the probability of the complete damage state.

Upon completion of an E-RVS screening of a population of buildings, preliminary prioritization of potentially vulnerable buildings can be determined using the Probability of Complete Damage (CODA) values or the Life Safety Risk Index (LSRI) which indicates the probability of collapse at the local MCE. As with RVS Final Scores, users/owners may set whatever cut-off scores they deem appropriate for their specific facilities. As one possible sorting scheme, we suggest that buildings with CODA values over 30%, from 10-to-30%, and less than 10% may be considered as very high, high and moderate priorities for further study and possible retrofit or replacement, respectively. This sorting scheme is illustrated in Figure 3.

Figure 3 Plan View Map of RVS and E-RVS Results for Western Oregon University Buildings

Table 19 E-RVS Results for Western Oregon University Buildings

Enhanced Rapid Visual Screening (E-RVS): DOGAMI Earthquake Life Safety Risk Assessment for Oregon Version 1.01

Organization: Western Oregon University

County: Date: City: Monmouth, Oregon 97361 2/5/2007 Contact Person: Contact Telephone Contact E-mail:

Building Name **Building Location**

or Address

Morrow Multnomah **Polk** Polk Sherman Tillamook

RM2

C2URM

C3C2C2RM2

C2RM2

C2C3C2C2C2RM2

PC1

RM1
RM2
URM
URM
C2URM
C1

Seismicity Region:
HIGH
Area Building (sf)
Built Year
Building Use

pancy Occu- Peak

Rehab Plan? Other

Building Type RVS

High Low Mid Rise Rise
Rise

Type Soil

Score Final RVS
S

50 of 2/3rds PGA

2% Years in

Probability of Complete Damage E-RVS Final Score S
Life Safety Risk Index

ITC 42,365 1915 >250 Mid
D 0.5 0.28 **1.2 70% 7.00**
Education 34,752 1965 >250 Low
D 0.2 0.28 **0.9 99% 13.00**
PE and Wolverton Pool 36,600 1936 >250 Low
D -0.5 0.28 **0.8 99% 15.00**
Smith Music Hall 14,315 1958 >250 High
D 1.2 0.28 **1.8 17% 1.74**
Natural Sciences 47,109 1969 >250 Low
D 2.2 0.28 **3.1 1% 0.08**
Stadium 11,090 1980 >250 Low
D 2.2 0.28 **3.1 1% 0.08**
Physical Plant 30,108 1960 Low
D 2.2 0.28 **3.1 1% 0.08**
Werner University Cntr. 33,045 1960 >250 Low
D 1.7 0.28 **2.5 2% 0.28**
Arbuthnot Hall 35,182 1961 Low
D 1.2 0.28 **2.0 8% 0.99**
Maaske Hall 22,260 1955 Low
D 1.7 0.28 **2.5 2% 0.28**
Butler Hall Dorm 5 24,641 1964 >250 Mid
D 0.7 0.28 **1.2 50% 6.50**
Gentle Hall Dorm 6 24,619 1966 >250 Low
D 1.4 0.28 **2.2 5% 0.61**
Barnum Hall Dorm 24,550 1968 >250 Low
D 1.4 0.28 **2.2 5% 0.61**
Landers Hall Dorm 8 55,925 1970 >250 Low
D 1.4 0.28 **2.2 5% 0.61**
Valsetz Dining Hall 48,022 1971 >250 Low
D -0.1 0.28 **0.9 99% 13.00**
PE Building New 62,468 1971 >250 Low
D 1.9 0.28 **2.8 1% 0.17**
Rice Auditorium 27,667 1976 >250 Low
D 0.7 0.28 **1.4 29% 3.75**
Police Academy 24,712 1988 >250 Low
D 1.7 0.28 **2.5 2% 0.28**
Administration Bldg 25,000 1936 >250 Mid
D -0.5 0.28 **0.8 99% 15.00**
Maple Hall 4,603 1900 Low
D 1.0 0.28 **1.8 11% 1.68**
HSS Humanities 36,799 1964 >250 Low
D 0.7 0.28 **1.4 29% 3.75**
Todd Hall 36,799 1912 >250 Mid

D 0.5 0.28 **1.2 42% 6.26**
Academic Programs 42,900 1951 >250 Low
D -0.3 0.28 **0.9 99% 13.00**

4.2 Example 2: Selected Buildings from Six Universities

A second example of the application of the E-RVS methodology to buildings at six university campuses Oregon is shown below in Table 20. Five of these locations are in the RVS high seismicity region, with one in the moderate seismicity region.

The E-RVS Final Scores are systematically higher than the RVS scores because the ground motions at all of these sites (except EOU) are lower than the median ground motions for the high or moderate seismicity region and because the E-RVS adjustments for soil types C and D are smaller than the RVS score modifiers for these soil types.

Table 20 E-RVS for Selected Buildings at Six Oregon Universities

Building Name

RVS Building Type
Low Rise Mid Rise High Rise
RVS Final Score S
2/3rds of 2% in 50 Years PGA

Probability
Life of Complete Damage
Safety Risk Index SOU Churchill C2 Low D -0.3 0.23 High **0.9 99% 13.00** WOU HSS C2 Low D 0.7 0.28 High **1.4 29% 3.75** WOU PE-Pool URM Low D -0.5 0.28 High **0.8 99% 15.00** PSU Lincoln S5 Low D -0.1 0.31 High **1.1 99% 8.00** PSU Stott C2 Low D 2.2 0.31 High **2.9 1% 0.12** PSU Science II C2 Mid D 2.6 0.31 High **3.3 <1% 0.05** UO Fenton URM Mid C 0.7 0.23 High **1.3 30% 4.54** UO Condon URM Low C 0.7 0.23 High **1.3 30% 4.54** UO Straub C2 Mid C 1.3 0.23 High **2.1 8% 0.78** OSU Nash S4 Mid D 1.1 0.28 High **1.8 30% 1.51** OSU Dearborn S1 Mid D 0.9 0.28 High **1.6 52% 2.61** OSU Sackett S1 Low D 0.7 0.28 High **1.4 52% 4.18** OSU Finley C2 Low D 1.2 0.28 High **2.0 10% 1.03** OSU Callahan RM2 Low D 1.2 0.28 High **2.0 10% 1.03** EOU Inlow C2 Low C 0.4 0.12 Moderate **1.1 55% 7.20**

SOU: Southern Oregon University WOU: Western Oregon University PSU: Portland State University UO: University of Oregon OSU: Oregon State University EOU: Eastern Oregon University

RVS Seismicity Region Soil Type

E-RVS Final Score S

4.3 Discussion of Oregon University System Applications

In Oregon, the RVS and DOGAMI E-RVS methods will continue to be applied to support state funding requests for seismic upgrades to state-owned university buildings. In late 2004, seismic upgrade needs in terms of RVS scores were proposed into the Oregon University System (OUS) state budget request along with deferred maintenance and energy efficiency scores. In the 2005-07 Legislature, eight million dollars were appropriated towards seismic upgrades. This was the first time state seismic funds were systematically appropriated in the OUS budget.

This E-RVS method was developed in time to be used in the 2007-09 OUS budget request. It allowed OUS to improve their budget requests by better prioritizing the seismic risk and providing transparent seismic deficiency scores so that decision makers could more easily understand the requests.

In November 2006, Governor Ted Kulongoski recommended $26 million to the 2007-09 Legislature in his budget for seismic upgrades of six high risk university buildings. These buildings were integrated in the OUS 2007-09 budget request with a needs matrix showing scores developed using the E-RVS method alongside deferred maintenance and energy efficiency scores. Specifically, the Governor recommended:

> $4.123 million for Western Oregon University's Humanities and Social Sciences, of which $0.952 million is for seismic improvements;
>
> $15.575 million for Oregon State University's Nash Hall, of which $3.834 million is for seismic improvements;
>
> $29.218 and $26.309 million for Portland State University's Lincoln Hall and Science Building II, of which $9.819 and $4.799 million are for seismic improvements, respectively; $8.072 million for the University of Oregon's Fenton Hall, of which $3.691 million is for seismic improvements; and $6.242 million for Eastern Oregon University's Inlow Hall, of which $1.195 million is for seismic improvements.

4.4 Future Applications in Oregon

In Oregon, other public buildings including kindergarten through high schools, community colleges, fire stations, police stations, hospitals and emergency operation centers are being screened using the RVS (FEMA, 2002a) method. This screening is being conducted by DOGAMI as part of a statewide needs assessment mandated by 2005 Senate Bill 2. We anticipate that the DOGAMI E-RVS method will be applied to the traditional RVS scores in Spring 2007. The final

statewide needs assessment will be issued on July 1, 2007 and will be publicly available.

Pending funding and as the field testing of the methodology progresses, additional comparisons and enhancements may be made by DOGAMI or others.

5.0 Future Improvements to Rapid Visual Screening

The enhancements made in the DOGAMI E-RVS methodology to the RVS methodology, especially calculating the probability of collapse at the local MCE instead of by seismicity regions, improve the accuracy of results. We suggest that these enhancements should be incorporated into future versions of the RVS methodology.

Given the large dispersion in the meaning of RVS Final Scores that arises because of the large variation in seismic hazard level within some counties and the even larger variation in seismic hazard level within the RVS-defined seismicity regions, an upgrade of the RVS methodology to base Final Scores on local MCEs is essential. This refinement would improve the accuracy and meaningfulness of RVS results and is an important refinement for the RVS methodology.

There are several other aspects of the existing RVS methodology where additional enhancements appear desirable including:

1) Re-evaluating Score Modifiers for reasonableness, including both the structural characteristics Score Modifiers and the soil-rock Score Modifiers,
2) Replacing the present linear combination of Score Modifiers with a more sophisticated method, including perhaps a simple root mean square combination or sorting the Score Modifiers by importance and using engineering judgment to weight the Score Modifiers’ contributions to the Final Score.
3) Incorporation of state-specific information on building code history, benchmark years, and local practices.

RVS Final Scores are, in effect, fragility curves for the complete damage state because they determine the probability of collapse at a defined level of ground shaking. The entire RVS Score calculation would be more transparent and understandable both to developers and to users if the fragility curves were explicit rather than implicit. The Basic Structural Hazard Score can be expressed directly as a fragility curve for the complete damage state, with Score Modifiers explicitly as adjustments to the fragility curve.

This approach would facilitate the re-evaluation of Score Modifiers and the improvement of the mathematics for combining Score Modifiers noted above by making it easier to evaluate the reasonableness of final scoring results. In contrast, the meaning and reasonableness of the present logarithmic Score Modifiers are not evident, even to many experienced structural engineers. For example, a given building with Score Modifiers of -0.6, -0.8, -.0.4 and -1.2 might have a Final Score of 1.2. Determining whether or not this Final Score is “reasonable” is more difficult than evaluating the reasonableness of a median PGA of, for example, 0.25 g, for the complete damage state because median PGAs for fragility curves can be compared directly to consensus HAZUS fragility curves for typical buildings.

Expressing RVS results in terms of fragility curves would also facilitate comparison of results with consensus HAZUS (FEMA, 2006) fragility curves for typical buildings.

6.0 Conclusions and Caveats

The DOGAMI E-RVS enhancements to the RVS method improve the accuracy and usability of the RVS method. Nevertheless, it is important to remember than E-RVS and RVS are preliminary screening tools – based on the limited information available from a sidewalk survey (or brief interior inspection). Thus, the primary use of E-RVS or RVS scores is to sort a population of buildings into those that require further engineering study and those that probably have acceptable seismic performance.

7.0 Acknowledgments

During the course of this project, the preliminary results were repeatedly reviewed by Bob Simonton of OUS for usefulness and application. The ultimate method recommended in this paper reflects modifications based on Mr. Simonton’s insights, especially concerning ease of integration in the state budget requests and understanding among decision makers. John Mester, Stanford University, provided technical reviews of the algorithms of the E-RVS methodology, including the calculations for the CODA and LSRI scores and the Oregon seismic hazard calculator. Paul Finke of Western Oregon University reviewed the results of the Western Oregon University pilot study.

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