CALIFORNIA INSTITUTE OF TECHNOLOGY

EARTHQUAKE ENGINEERING RESEARCH LABORATORY

A SURVEY OF BRIDGE PRACTITIONERS TO RELATE DAMAGE TO CLOSURE

BY

KEITH A. PORTER
CALIFORNIA INSTITUTE OF TECHNOLOGY

REPORT NO. EERL 2004-07

A REPORT ON RESEARCH SUPPORTED BY THE
PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

PASADENA, CALIFORNIA

AUGUST, 2004

A REPORT ON RESEARCH SUPPORTED BY THE
PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER
UNDER THE SUPERVISION OF KEITH A. PORTER

A SURVEY OF BRIDGE PRACTITIONERS TO RELATE DAMAGE TO CLOSURE

Keith A. Porter
California Institute of Technology, Pasadena, CA

Abstract

The Pacific Earthquake Engineering Research (PEER) Center's second-generation performance-based earthquake engineering (PBEE) methodology is intended in part to model highway bridge performance in terms of collapse, closure, repair duration, speed or load limitations, and possibly other performance measures. Some of these are difficult to model, particularly closure decisions where the engineering evidence of safety is inconclusive and must be supplemented by the inspector's judgment. This paper presents results of a limited, initial survey of department of transportation (DOT) engineers' beliefs about the relationship between physical damage and closure. The initial survey addresses a common class of reinforced-concrete bridges. The author and others developed and administered to a select, nationwide group of DOT engineers a one-page, multiple-choice survey form with expert self-rating, asking the engineers to relate ten damage measures (DM) to four closure levels. The DMs include approach settlement, offsets at abutments and expansion joints, flexural and shear cracks in beams, columns, shear keys, and backwalls. The performance levels considered are: leave open, close briefly for quick repairs, close for an extended period, and reduce speed. The survey results are analyzed to produce a number of preliminary relationships between damage and post-earthquake decisions by inspectors, relationships that can be used in probabilistic seismic performance evaluation in PEER's developing PBEE methodology. This preliminary test of a survey form also yielded insight into a number of desirable improvements for a second round of survey, possibly to be administered via the Internet early in 2004.

CONTENTS

FIGURES

TABLES

1. INTRODUCTION

Performance-based earthquake engineering (PBEE) has developed substantially since the mid-1990s. The basic idea is that designs can be analyzed to assess the performance of an engineered facility such as a building or a bridge in terms of direct interest to stakeholders, such as post-earthquake operability. Important examples for buildings include Vision 2000 (SEAOC, 1995), FEMA 273 (1997), and FEMA 356 (ASCE 2000). Caltrans' Seismic Design Criteria (1999) offers a related approach for bridges.

Much remains to be accomplished in the development of PBEE, however. As Hamburger and Moehle point out (2000), existing guidelines tend not explicitly to estimate the performance of the system as a whole and do not adequately treat uncertainties in the relationship between ground motion intensity and performance. Because damage and system performance are often not explicitly calculated, engineers may think of engineering demands such as member forces, deformations, or ductility *as* performance, rather than merely as indicators of performance. As used here, performance is measured in terms of stakeholders' direct interests such as repair costs, casualties, and loss-of-use duration ("dollars, deaths, and downtime").

The Pacific Earthquake Engineering Research (PEER) Center is in the process of developing a second-generation PBEE methodology that seeks to address these two general needs. In the PEER methodology, the analyst begins by defining a bridge or building of a particular design at a particular location, and by establishing one or more levels of an intensity measure (*IM*) at which performance is to be evaluated. *IM* can be measured a variety of ways, such as damped elastic spectral acceleration at some reference period of interest. One or more structural analyses are performed to estimate the engineering demand parameters (*EDP*) that the *IM* will impose on the facility. *EDP*s measure member forces, deformations, and displacements. Given the structural response, the analyst estimates the physical damage in terms of one or more damage measures (*DM*). These are then related to the system's overall seismic performance via one or more decision variables (*DV*) such as dollars, deaths, and downtime. The reader is referred to Porter (2003) for an overview of the PEER methodology.

Much of PEER's PBEE framework has been filled in with a detailed probabilistic methodology. Missing from the bridge-analysis methodology however is the means to assess *DV* as a function of *DM*. Bridge *DV*s have been only partially specified, and little work has been performed to relate bridge damage to performance. The present study probes the relationship between *DM* and one *DV* of interest, namely, whether a bridge will be closed after an earthquake, and if so, for how long.

Note that this study does not examine the normative question what the inspector *should* do, but rather what he or she is likely to do when confronted with a bridge with various symptoms of damage. This initial exploratory study examines only a single category of bridge: a multi-span highway bridge with precast, prestressed AASHTO-Caltrans I-girders on cast-in-place single-column bents on a foundation of driven prestressed concrete piles and cast-in-place pilecaps. The bridge category is further limited to non-critical bridges, i.e., with modest traffic demands or where alternative routes are readily available. However, it offers a pattern for exploring the *DM-DV* relationship for any number of other bridge categories.

2. METHODOLOGY

It is often unclear whether a damaged bridge that has not actually collapsed should be closed. In such situations, the inspector examining a bridge may have to exercise a great deal of judgment, and the judgment of different inspectors can vary substantially. To create a model of such a situation, it is helpful to begin by parameterizing the features that inspectors consider, and encoding the judgment of several of them.

To do this, the author prepared a single-page survey instrument in a format suggested by Eberhard (2003), and solicited the participation of bridge engineers from around the United States to exercise it. The instrument is in table form. Row headers are *DM*s that are most likely of interest. Column headers and ranges of possible corresponding *DV* values. Each cell of the table offers two or more choices for the maximum allowable value of *DM* that is consistent with the given level of *DV*. An example is given in Table 1. The circles represent the judgment of a hypothetical respondent. The circle in the upper-left-hand corner of the form means that the respondent judges that if the approach settlement were in the range of 1-3 inches, the bridge could remain open, but that settlement of greater than 3 inches would require at least brief closure. The circle in the upper right similarly suggests that the bridge could be reopened within 3 days if as much as 3 to 6 inches of approach settlement occurred.

Table 1. Sample portion of survey form with hypothetical responses

Decision → **Damage ↓**	**No closure**	**Close 1-3 days**
Settlement of approach	<1 in (1-3 in) 3-6 in >6 in	<1 in 1-3 in (3-6 in) >6 in
Vertical offset at abutment	(<1 in) 1-3 in 3-6 in >6 in	<1 in (1-3 in) 3-6 in >6 in

The initial list of *DM*s was based on discussion between PEER researchers and several Caltrans engineers involved in the seismic evaluation and retrofit of a bridge fitting this description, in which the Caltrans engineers described the kinds of physical damage they considered in their analysis of the potential future performance of the bridge. This list was reviewed by several PEER, MAE, and MCEER researchers (Eberhard, Conte, DesRoches, Mahin, Buckle, and others), who offered suggestions for modification and improvement. In recognition that survey respondents might offer additional *DM*s, the form includes room in for two more *DM*s. The bridge-closure *DV* is discretized into a few discrete ranges, again leaving room for survey respondents to add more.

The survey form includes brief instructions; a header that requested the respondent's name, agency or affiliation, general area of expertise, an identifier for the bridge category that the respondent was considering; and self-judgment of expertise with this bridge category.

This last is based on the observation that one might want to consider the judgment of experts differently from respondents with little or no familiarity with the bridge category in question.

The final form includes 10 *DM*s related to approach settlement; horizontal and vertical offset at the bridge-abutment interface; horizontal and vertical offset at expansion joints; beam and column flexural and shear crack widths; beam and column spalling; beam and column rebar buckling, fracture, or pullout; and shear key or backwall shear cracking or spalling. The list could have been extended to great detail, and this was urged by some researchers. However, the author judged that the practitioners would be less likely to complete a multiple-page form than a single-page one, and so limited the *DM*s to ten.

The final form includes four ranges of the closure *DV*: no closure; close 1-3 days; close more than 3 days; and leave open, but limit traffic to reduced speeds. Again, more levels could have been added, but at the cost of a multiple-page form or of surrendering the opportunity for respondents to define other performance levels of interest. The form was submitted to a select group of bridge engineers from departments of transportation around the United States, during the First Tri-Center User Workshop on the Application of Earthquake Loss Estimation Methodologies for Transportation Highway Systems, June 24-25, 2003, Hilton Port of Los Angeles/San Pedro, San Pedro, CA. Twelve respondents completed the form for the subject bridge type. Of these, six described themselves as having expertise of 4 or 5 on a 1-to-5 scale (with 5 being expert). The form is reproduced here in the appendix.

3. RESPONSES, ANALYSIS, AND RESULTS

3.1 SURVEY RESPONSES

Table 2 presents statistics of survey responses by DOT engineers who self-rated their expertise as 4 or 5 (expert) on a 1-to-5 scale. In several cases at least half of respondents did not provide a judgment of the maximum value of the *DM* corresponding to the given level of *DV*; these are shown in gray, to indicate that they are of limited value.

Table 2. Survey responses, expertise levels 4 and 5

DM1: Settlement of approach

DM	No closure	Close 1-3 days	Close > 3 days	Reduced speed
<1 in	1	0	0	0
1-3 in	3	1	0	3
3-6 in	2	3	1	2
>6 in	0	1	3	0
no response	0	1	2	1

DM2: Vertical offset at abutment

DM	No closure	Close 1-3 days	Close > 3 days	Reduced speed
<1 in	0	0	0	1
1-3 in	3	1	0	2
3-6 in	1	3	1	0
>6 in	0	1	3	1
no response	2	1	2	2

DM3: Horizontal offset at abutment

DM	No closure	Close 1-3 days	Close > 3 days	Reduced speed
<1 in	0	0	0	0
1-3 in	2	0	0	1
3-6 in	3	1	0	2
>6 in	1	3	5	2
no response	0	2	1	1

DM4: Vertical offset at expansion joint

DM	No closure	Close 1-3 days	Close > 3 days	Reduced speed
<1/2 in	2	0	0	0
1/2 in-1 in	4	1	0	1
>1 in	0	3	5	2
no response	0	2	1	3

DM5: Horizontal offset at expansion joint

DM	No closure	Close 1-3 days	Close > 3 days	Reduced speed
<1/2 in	0	0	0	0
1/2 in-1 in	4	0	0	1
>1 in	1	4	3	2
no response	1	2	3	3

Table 2. Survey responses, expertise levels 4 and 5**, cont.**

DM6: Maximum beam or column flexural crack width

DM	No closure	Close 1-3 days	Close > 3 days	Reduced speed
<1/32 in	3	0	0	0
1/32-1/8 in	3	3	1	2
>1/8 in	0	1	5	1
no response	0	2	0	3

DM7: Maximum beam or column shear crack width

DM	No closure	Close 1-3 days	Close > 3 days	Reduced speed
<1/32 in	4	0	0	0
1/32-1/8 in	2	3	1	1
>1/8 in	0	1	5	1
no response	0	2	0	4

DM8: Concrete beam or column spalling

DM	No closure	Close 1-3 days	Close > 3 days	Reduced speed
No	1	1	2	2
Yes	2	2	1	0
no response	3	3	3	4

DM9: Beam or column rebar buckling fracture pullout

DM	No closure	Close 1-3 days	Close > 3 days	Reduced speed
No	4	0	1	0
Yes	0	3	4	2
no response	2	3	1	4

DM10: Shear key or backwall shear cracking or spalling

DM	No closure	Close 1-3 days	Close > 3 days	Reduced speed
No	0	1	1	0
Yes	3	2	0	1
No response	3	3	5	5

3.2 ANALYSIS OF SURVEY RESPONSES

Each cell of the form represents the respondent's judgment of the maximum range of the *DM* that would be permissible for that level of *DV*. A greater value of the *DM* would cause the bridge to exceed that level of *DV*, in the judgment of that respondent. One can use these judgments to estimate the probability that an inspector will make one of various closure decisions as functions of the *DM* he or she observes in a similar bridge. That is, one can create fragility functions for *DV* as a function of *DM*. (A fragility function in general gives the probability of some undesirable outcome given some input excitation.) In the present case, the undesirable outcome is that the *DV* exceeds the value stated in the column header. The excitation is the level of the *DM* stated in the row header.

Scalar damage measures. Two approaches are necessary for generating these fragility functions: one for *DM*s that are scalar measures such as a measure of approach settlement, another for binary (true/false) measures such as the occurrence of spalling. The sample statistics of probability are the individual experts' judgments of the upper bound of *DM* corresponding to a given level of DV. That is, let

x_k = maximum value of DM_i corresponding to $DV = dv_j$ as judged by expert k

N = number of respondents

Then if one assumes that the fragility function $P[DV > dv_j \mid DM_i = x]$ can be adequately approximated as a lognormal cumulative distribution function (a common assumption), one can estimate the fragility function by

$$\mu_X = \frac{1}{N}\sum_{k=1}^{N} x_k \tag{1}$$

$$\sigma_X^2 = \frac{1}{N-1}\sum_{k=1}^{N}(x_k - \mu)^2 \tag{2}$$

$$\delta_X = \frac{\sigma_X}{\mu_X} \tag{3}$$

$$\hat{x} = \frac{\mu_X}{\sqrt{1+\delta_X{}^2}} \tag{4}$$

$$\beta_X = \sqrt{\ln\left(1+\delta_X{}^2\right)} \tag{5}$$

$$P\left[DV > dv_j \mid DM_i = x\right] = \Phi\left(\frac{\ln\left(x/\hat{x}\right)}{\beta_X}\right) \tag{6}$$

where

DV = the uncertain value of the decision variable of interest, e.g., closure duration

dv_j = a particular value of DV, indexed by j, e.g., no closure

DM_i = the uncertain value of damage measure i, e.g., maximum beam or column flexural crack width

x = a particular value of DM_i, e.g., 1/8 in.

X = the uncertain upper limit of DM_i corresponding to $DV = dv_j$

μ_X = mean value of X

σ_X = standard deviation of X

δ_X = coefficient of variation of X

$\hat{x}$ = median of X, i.e., the value of X with 50% probability of being exceeded

β_X = logarithmic standard deviation of X

$P[A \mid B]$ = probability of A given B

Note that each (i, j) pair would have its own fragility function, i.e., its own distribution of $X_{i,j}$ and therefore its own $\hat{x}$ and β_X, but the subscripts on X are dropped here for brevity. For example, consider the fragility function for $(i, j) = (1, 1)$, i.e., for at least some bridge ($DV > dv_1$), given degree of approach settlement, DM_1. As shown in Table 2, one respondent felt that the maximum allowable level of DM_1 for no closure is 1 in; three judged that DM_1 could be as great as 3 inches without requiring bridge closure, and two felt that as much as 6 inches of settlement could be tolerated without closing the bridge. The mean value of $X_{1,1}$ is thus 3.7 in; the standard deviation, 2.0 in.; the median, 3.2 in.; and the logarithmic standard deviation, 0.50. Figure 1 shows the data of the expert respondents' judgments (circles), along with the fragility function fit to them (smooth curve).

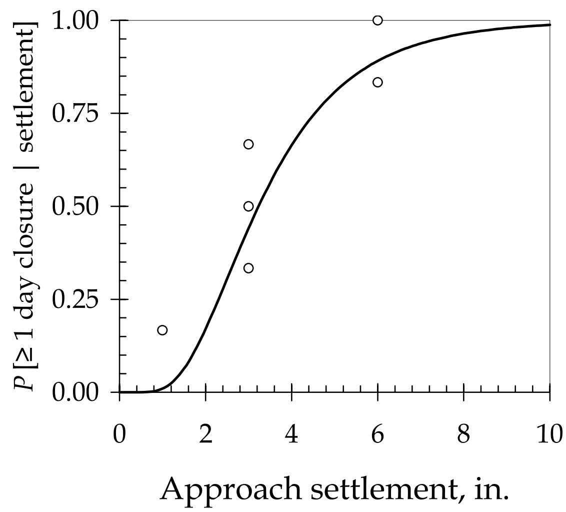

Figure 1. Example fragility function

Binary damage measures. A different approach is needed for binary (true/false) damage measures. If n of N total respondents feel that the damage measure must be "false" to be associated with a performance level dv_j, then the probability that $DV > dv_j$, given $DM_i = true$ would be estimated as n/N, that is,

$$P[DV > dv_j \mid DM_i = \text{true}] = n/N \quad (7)$$

3.3 RESULTS

Evaluating Equations (1) through (5) for data in Table 2 yields the parameters shown in Table 3, the final fragility functions for the *DM-DV* relationships examined here.

The question remains, how are multiple fragility functions to be evaluated and combined to produce a probability distribution of *DV* given a set of *DM*? For example, suppose a particular bridge were estimated to have 2 inches of approach settlement, 2 inches of vertical offset at the abutment, 4 inches of horizontal offset at the abutment, etc. Each of 10 *DM*s has four fragility functions to be evaluated, for a total of forty probabilities $P[\text{DV} > dv_j \mid DM_i]$. The DOT engineers were not asked to evaluate *DV* for vectors of *DM*, but clearly an inspector examining a bridge with a variety of earthquake damages must synthesize the evidence to decide on one value of a *DV*. The difficulty is that there are too many possible vectors *DM* to gather several experts' judgment on *DV* for each combination.

Thus, the results presented here cannot be used to support a definitive solution to this problem. However, consider a possible approach that could be spot-checked for a limited number of sample vectors. Let $\underline{DM}$ denote the vector $[DM_1, DM_2, .. DM_{10}]^T$. One could hypothesize that the worst damage measure would control the probability of closure, i.e.,

$$P[DV > dv_j|\underline{DM}] = \max_i(P[DV > dv_j|DM_i]) \tag{8}$$

The hypothesis could be tested by offering a number of experts sample vectors of $\underline{DM}$, having them assign a performance level *DV* based on each damage vector, and comparing Equation (8) with the statistics of the experts' judgment.

Table 3. Parameters of DM-DV relationships

DM1: Settlement of approach, in.

	Close at least briefly	Close at least 3 days
μ_X	3.67	5.50
σ_X	1.97	3.14
δ_X	0.54	0.57
$\hat{x}$	3.23	4.78
β_X	0.50	0.53

DM2: Vertical offset at abutment, in.

	Close at least briefly	Close at least 3 days
μ_X	3.75	5.50
σ_X	1.50	3.14
δ_X	0.40	0.57
$\hat{x}$	3.48	4.78
β_X	0.39	0.53

DM3: Horizontal offset at abutment, in.

	Close at least briefly	Close at least 3 days
μ_X	6.00	7.00
σ_X	3.29	3.90
δ_X	0.55	0.56
$\hat{x}$	5.26	6.12
β_X	0.51	0.52

DM4: Vertical offset at expansion joint, in.

	Close at least briefly	Close at least 3 days
μ_X	0.83	1.17
σ_X	0.26	0.65
δ_X	0.31	0.56
$\hat{x}$	0.80	1.02
β_X	0.30	0.52

DM5: Horizontal offset at expansion joint, in.

	Close at least briefly	Close at least 3 days
μ_X	1.20	1.33
σ_X	0.45	0.60
δ_X	0.37	0.45
$\hat{x}$	1.12	1.22
β_X	0.36	0.43

Table 3. Parameters of DM-DV relationships, cont.

DM6: Maximum beam or column flexural crack width, in.

	Close at least briefly	Close at least 3 days
μ_X	0.078	0.156
σ_X	0.051	0.063
δ_X	0.66	0.40
$\hat{x}$	0.065	0.145
β_X	0.60	0.39

DM7: Maximum beam or column shear crack width, in.

	Close at least briefly	Close at least 3 days
μ_X	0.063	0.104
σ_X	0.048	0.067
δ_X	0.77	0.64
$\hat{x}$	0.049	0.088
β_X	0.69	0.59

DM8: Concrete beam or column spalling

	Close at least briefly	Close at least 3 days
$P[dv \mid DM_8 = true]$	0.33	0.33

DM9: Beam or column rebar buckling fracture pullout

	Close at least briefly	Close at least 3 days
$P[dv \mid DM_9 = true]$	1.00	1.00

DM10: Shear key or backwall shear cracking or spalling

	Close at least briefly	Close at least 3 days
$P[dv \mid DM_{10} = true]$	0.67	0.67

4. CONCLUSIONS

A survey was used to probe the judgment of engineers from departments of transportation around the United States on decision-making for highway bridge closure based on physical damage. Such a survey will be useful in modeling bridge performance in cases where the engineering evidence of safety is inconclusive and must be supplemented by an inspector's judgment. The engineering evidence is parameterized here with 10 damage measures (*DM*) that range from approach settlement to cracking or spalling in shear keys or backwalls. The survey examined a single decision variable: whether to close a bridge or to reduce traffic speed based on the physical damage, and whether the closure (if it occurred) would be brief (less than 3 days) or extended. The survey probed the engineers' judgment for a single class of highway bridge that is common in the western United States, namely, prestressed AASHTO-Caltrans girders on cast-in-place, reinforced concrete, single-column bents founded on reinforced concrete pilecaps on groups of prestressed driven piles.

The survey produced 12 responses, of which six were from self-described experts who rated their familiarity with the sample class of bridge as 4 or 5 on a 1-to-5 scale of expertise. In most cases, the experts provided responses that could be used to create decision-making fragility functions that relate the probability of closure to the 10 damage measures. The resulting fragility functions give the probability that the bridge will be closed at least briefly or for an extended period, given the observed physical damage. The fragility functions are of the form

$$P[DV > dv_j|\underline{DM}] = max_i(P[DV > dv_j|DM_i]) \quad (8)$$

where $\underline{DM} = [DM_1, DM_2, \ldots DM_{10}]^T$, $P[DV > dv_j \mid DM_i]$ is given by Equation (6) or by Equation (7), as appropriate, and each (i, j) pair has its own associated parameters as shown in Table 3. A follow-on survey is planned for the purpose of gathering a larger sample of responses, and to probe the interaction of different damage measures on the closure decision.

5. ACKNOWLEDGMENTS

Support of this work was provided in part by the Earthquake Engineering Research Centers Program of the National Science Foundation, under award Number EEC-9701568 through the Pacific Earthquake Engineering Research Center (PEER). The survey forms were completed by participants of a workshop co-sponsored by PEER, the Mid-America Earthquake (MAE) Center, and the Multidisciplinary Center for Earthquake Engineering Research (MCEER). Their support is gratefully acknowledged. The author thanks the engineers from the state departments of transportation who responded to the survey. Thanks also to Reggie DesRoches, who solicited input from several DOT practitioners at the workshop. As noted in the text, Marc Eberhard suggested the format of the survey table. Drs Eberhard, DesRoches, Joel Conte, Sashi Kunnath, and Steve Mahin offered advice on the content of the survey form. Their assistance is gratefully acknowledged.

6. REFERENCES CITED

American Society of Civil Engineers, 2000, *FEMA-356: Prestandard and Commentary for the Seismic Rehabilitation of Buildings,* Federal Emergency Management Agency Washington, DC.

California Department of Transportation (Caltrans), 1999, *Caltrans Seismic Design Criteria Version 1.1,* Sacramento, CA, 106 pp. www.peertestbeds.net/Hbt/sdc.pdf

Eberhard, M.E., 2003, personal communication.

Federal Emergency Management Agency, 1997, *FEMA-273: NEHRP Guidelines for the Seismic Rehabilitation of Buildings*, Washington, DC, 386 pp.

Hamburger, R.O. and J.P. Moehle, 2000, "State of Performance-Based Engineering in the United States," *2nd U.S.-Japan Workshop on Performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures*, Sapporo, Japan, September 2000, http://peer.berkeley.edu/moehle/papers/State_of_PBEE_in_US.pdf

Porter, K.A., 2003, "An Overview of PEER's Performance-Based Earthquake Engineering Methodology," *Proc. Ninth International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP9)*, July 6-9, 2003, San Francisco, CA. Civil Engineering Risk and Reliability Association (CERRA), http://keithp.caltech.edu/publications.htm

Structural Engineers Association of California (SEAOC), 1995, "Vision 2000, conceptual framework for performance-based seismic design," *Recommended Lateral Force Requirements and Commentary, 1996, 6th Edition*, Sacramento, CA, 391-416.

APPENDIX: FIRST-ROUND SURVEY INSTRUMENT

This is a survey form to elicit from bridge design, operations, and post-earthquake inspection professionals information about seismic damage symptoms, closure decisions, and quantitative relationships between the two. Each form is intended to reflect one expert's opinions regarding one subcategory of highway bridge. The attached form is limited to subcategories of concrete girder bridges. Other types would have different damage measures.

Instructions:

1. *Complete the summary information.* Write your name and affiliation on the form, and circle the field that most closely matches your area of greatest expertise. You will be asked to consider a category of highway bridges. Write the category title and circle your self-judged level of familiarity with this category of bridge, from 1 (no knowledge) to 5 (expert).

2. *Review the damage measures.* A damage measure is a measurement of some symptom of physical damage. It might be observable by an inspector after an earthquake, or modeled in a computer simulation but not easily observable, but in either event it is a physical state of a bridge component such as cracking or spalling, as opposed to a structural-response parameter such as peak shear stress or hysteretic energy. Please consider the list of damage measures (row headings on the left-hand side of the table). These are intended to reflect the principal symptoms of seismic damage that affect post-earthquake performance. That is, they are the damage symptoms that would or should drive the decision to open, close, repair, or replace a bridge. If there are important missing damage measures, add up to two in the blank row headings.

3. *Review the decision variables.* Consider the list of post-earthquake decisions (column headings at the top of the table). These are intended to reflect general levels of post-earthquake bridge performance. If there are important missing decision alternatives (e.g., reduced speed, reduced load allowance), add up to two in the blank column headings.

4. *Judge the DM-DV relationships.* Cells of the table reflect levels of damage (rows) that could cause a DOT to take that action (columns). Please check or fill in the degree of damage that you think *should* be associated with that action. (Not what *currently* happens, or *could* happen, but what, if you were in charge, *should* happen.)

5. *Comment.* Provide any commentary on page 3. For example, you might provide advice regarding how this survey instrument might be enhanced or applied to maximize its usefulness, or about research that could complement it.

Name: ______________________________
Agency or affiliation: ______________________________
Area of expertise: Geotech Structural design Inspection or maintenance Traffic
Bridge category: ______________________________
Level of familiarity: 1 (none) 2 3 4 5 (expert)

What is the range of each damage measure that might lead to a particular decision?

Decision → Damage ↓	**No closure**	**Close 1-3 days**	**Close > 3 days**	**Reduced speed**		
Settlement of approach	<1 in 1-3 in 3-6 in >6 in	<1 in 1-3 in 3-6 in >6 in	<1 in 1-3 in 3-6 in >6 in	<1 in 1-3 in 3-6 in >6 in	<1 in 1-3 in 3-6 in >6 in	<1 in 1-3 in 3-6 in >6 in
Vertical offset at abutment	<1 in 1-3 in 3-6 in >6 in	<1 in 1-3 in 3-6 in >6 in	<1 in 1-3 in 3-6 in >6 in	<1 in 1-3 in 3-6 in >6 in	<1 in 1-3 in 3-6 in >6 in	<1 in 1-3 in 3-6 in >6 in
Horizontal offset at abutment	<1 in 1-3 in 3-6 in >6 in	<1 in 1-3 in 3-6 in >6 in	<1 in 1-3 in 3-6 in >6 in	<1 in 1-3 in 3-6 in >6 in	<1 in 1-3 in 3-6 in >6 in	<1 in 1-3 in 3-6 in >6 in
Vertical offset at expansion jt.	< ½ in ½ in-1 in >1 in	< ½ in ½ in-1 in >1 in	< ½ in ½ in-1 in >1 in	< ½ in ½ in-1 in >1 in	< ½ in ½ in-1 in >1 in	< ½ in ½ in-1 in >1 in
Horizontal offset at expansion jt.	< ½ in ½ in-1 in >1 in	< ½ in ½ in-1 in >1 in	< ½ in ½ in-1 in >1 in	< ½ in ½ in-1 in >1 in	< ½ in ½ in-1 in >1 in	< ½ in ½ in-1 in >1 in
Max. beam or column flexural crack width	< 1/32 in 1/32-1/8 in >1/8 in	< 1/32 in 1/32-1/8 in >1/8 in	< 1/32 in 1/32-1/8 in >1/8 in	< 1/32 in 1/32-1/8 in >1/8 in	< 1/32 in 1/32-1/8 in >1/8 in	< 1/32 in 1/32-1/8 in >1/8 in
Max. beam or column shear crack width	< 1/32 in 1/32-1/8 in >1/8 in	< 1/32 in 1/32-1/8 in >1/8 in	< 1/32 in 1/32-1/8 in >1/8 in	< 1/32 in 1/32-1/8 in >1/8 in	< 1/32 in 1/32-1/8 in >1/8 in	< 1/32 in 1/32-1/8 in >1/8 in
Concrete beam or column spalling	No Yes	No Yes	No Yes	No Yes	No Yes	No Yes
Beam or column rebar buckling, fracture, pullout	No Yes	No Yes	No Yes	No Yes	No Yes	No Yes
Shear key or backwall shear cracking or spalling	No Yes	No Yes	No Yes	No Yes	No Yes	No Yes

[A third sheet, blank except for the word "Commentary" at the top, followed this one.]