SEISMIC SCREENING OF BRIDGES IN NEW ZEALAND

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SUMMARY

New Zealand's stock of road bridges includes numerous structures that were designed before current seismic design procedures were introduced. Some of these structures, in particular, need to be assessed for possible seismic retrofitting. This paper describes a screening procedure that is being implemented to review all the state highway bridge stock, and to identify and prioritise, at acceptable cost, those structures that justify more detailed seismic analysis and assessment.

INTRODUCTION

Background

New Zealand is a lightly populated mountainous country. It has a well developed roading system with a total length of some 92,000 km, of which 10,500 km are state highways. The state highways are administered by the national roading authority, Transit New Zealand, while the local territorial authorities administer the local roads.

The country's stock of road bridges with spans exceeding 3 metres comprises approximately 2,500 structures on the state highway network and approximately 7,000 on the local authority roads. Much of the stock - 65 percent in the case of state highways - was built in the period 1930 to 1970. The total length of bridging amounts to 300 km, resulting in average bridge lengths of 50 metres and 20 metres on the state and local authority systems respectively. While a large proportion of the bridges comprise short single span structures, there are many multi-span bridges, with lengths up to 1,750 metres.

The seismicity of the most active parts of the country is similar to that of California with a magnitude 6 earthquake or greater occurring on average every year and a magnitude 7 or greater every 10 years. New Zealand bridge design for earthquake resistance has advanced significantly since about 1970. In this period understanding of structural dynamic behaviour and of methods to attain ductility of concrete members has improved and results of research have been translated into a form readily usable by designers.

Before 1970 structural integrity was recognised as an important design consideration, especially as a result of the Napier earthquake in 1931 - a Richter magnitude 7.8 event in the north east of the North Island. A Public Works Department design instruction dated 1933 required that "wherever possible the structure should be made monolithic, and where this is not possible all parts of the structure should be well tied together". Such design practices are evident in structures built since 1933 and there are few where spans are not interlinked. A feature of these structures, however, is the absence of special detailing for member ductility, and of the application of capacity design procedures, both of which are now important aspects of seismic design practice.

Past Policy on Seismic Retrofitting of Highway Bridges

Approximately 30% of the state highway bridge stock has been built since 1970. This represents a period of significant effort by the roading authority to upgrade the geometric standards of the roads and to replace substandard bridges for traffic loading or geometric requirements. In addition, urban motorway systems have been developed in the main cities. During this period funding was allocated primarily to raising the service standards of bridging rather than to seismic retrofitting. In cases where improved seismic performance could be

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achieved at small cost by combining retrofitting with improvements for service purposes, this was done. Examples are discussed in [Chapman 1991]. While there was an awareness that unacceptable seismic risk should be remedied, high risks of span collapse had generally been alleviated by the policy of interlinking spans from an early date.

Current Policy on Seismic Retrofitting of Highway bridges

Much of the new bridge construction is now complete and more emphasis is being placed on maintaining the stock. With progressive traffic growth the consequential cost of disruption by earthquake is increasing and attention is focusing on assessing these risks and taking appropriate action. Since 1990 seismic assessment and retrofitting has been concentrated on two of the major strategic structures on the state highway network – namely the Thorndon overbridge in Wellington and the Auckland Harbour bridge. The estimated replacement cost of these two structures together represents approximately 20% of the total replacement cost of all the state highway bridges, and it was clear that work should be implemented on them as soon as possible. Physical retrofit is now complete on the Thorndon bridge, and is in hand on the Auckland Harbour bridge.

While it was clear that detailed assessment was justified for the Thorndon and Auckland Harbour bridges, it was unclear how the priority for detailed seismic assessment should be assigned amongst the general bridge stock. Detailed assessment is expensive, and it is therefore important to identify those bridges for which it is not justified, and to prioritise the remainder. A staged process, similar to sieving with increasing degrees of fineness, is being followed. A seismic screening procedure was developed as the first stage, and is currently being implemented. The output from the procedure will be a list of bridges, in priority order, that are considered to justify detailed seismic assessment and, subsequently for some, seismic retrofitting. It is only after detailed assessment that it will be decided whether seismic retrofit should be undertaken.

At present bridges in eleven of the fourteen administrative regions are being screened, leaving the three regions of least seismic hazard for subsequent consideration. The contract for applying the screening procedure in each region of the state highways network has been negotiated with the consultant who holds the inspection contract for the bridges in that region. This has the advantage that the consultant is familiar with the structures involved. In practice, the inspections, and hence the screening, are shared between three consulting firms. Concentrating the work among a few specialists increases the probability of consistent overall results, as the conclusions of the screening depend largely on subjective judgements throughout the procedure.

Development of the Screening Procedure

Early development of the screening procedure has been described in [TNZ 1996]. Main stages comprised:

A pilot study, in which five typical bridge types designed in the 1930s to 1960s period were assessed to determine whether they represent a significant seismic risk to the integrity of the highway network. The study, and subsequent model testing, confirmed the expectation that bridges from this era possess a number of vulnerabilities with potential for causing bridge failure during strong earthquake shaking, although the tests showed some typical elements perform quite well.

A preliminary screening procedure was developed and was based only on allocating “score values” to a number of attributes that relate to the hazard at the bridge site, and the importance and vulnerability of the bridge. This was applied as a trial to the bridges on a 160km length of highway north of Wellington, which includes 29 bridges. Approximate structural analyses were carried out on the bridges to assess the probabilities and nature of likely seismic damage. Economic analyses were also undertaken to assess the economic impact of bridge damage, retrofit costs and repair costs for the 29 bridges. This study, which is reported in [TNZ 1996], showed that, while the preliminary screening procedure provided a general indication of priorities for more detailed analysis, more consideration of the risk and economics aspects needed to be included in the screening procedure. The screening procedure was therefore extended and refined.

THE ADOPTED SCREENING PROCEDURE

Description

The screening procedure is illustrated in Figure 1 and the following summary is from the Transit New Zealand Screening Manual [TNZ 1998]. The procedure requires inputs with increasing degrees of bridge and seismic specialisation as the steps are completed, and the number of bridges to be considered progressively reduces from one stage to the next:

- *Stage 1:* The Total Exclusion identifies those structures, such as culverts up to 3 metres span and most bridges that are programmed for replacement within five years, for which the risk of seismic damage is considered to be so low that assembly of drawings and further assessment are not necessary.

- *Stages 2 and 4:* The Assembly and Recording of Bridge Data forms the basis for the assessments and is undertaken by inspection personnel, who are most familiar with the bridges. They also assemble the sets of drawings, and, when available, photographs of the structures. By using their knowledge, the chance of the information being incorrect or incomplete is reduced. Data are assembled in two stages, to avoid gathering information that will not be required for those bridges that are excluded in Stage 3 of the procedure.

  The data assembled in Stage 2 are sufficient to enable the assessor to decide whether the structure meets the criteria that allow it to be excluded in Stage 3 from further parts of the screening procedure. Included are the recording of the type of soil on which the structure is located, and the level of risk of liquefaction to which the foundations are subjected.

  The data assembled in Stage 4 comprise information relevant to the assessment of the effects of traffic disruption – for example traffic use, length of detour, journey speeds, facilities crossed and services carried. This information is only collected for the bridges not excluded in Stage 3.

- *Stage 3:* In this stage, all bridges with unlinked spans are recorded for early retrofit of linkages. The Preliminary Screening also identifies those bridges for partial exclusion from the screening procedure, in that they clearly do not warrant further ranking because their size or form gives them inherent resistance to significant seismic damage. The bridges are initially identified as conforming to a list of criteria, subsequently confirmed by specialist review in Stage 7. The criteria for exclusion include:

  - Bridges designed after 1972, when current design criteria and methods were introduced;

  - Single span bridges with monolithic, or otherwise secure, abutment/span connections;

  - Multi-span bridges of three spans or fewer that also meet nine other criteria, such as limited risk of liquefaction, uniformity of spans, moderate pier height, limited skew and secure inter-span linkages.

- *Stage 5:* The Seismic Attributes Grade (SAG) is an arithmetically derived indicator value based on a combination of weighted "scores" covering several elements grouped by hazard, importance and vulnerability. The "scores" are assigned to each bridge being graded, according to its attributes. Ranking by this indicator alone is not sufficiently reliable, but the SAG has been found to be useful in helping with the judgement-based final stage of the ranking procedure to prioritise the bridges for detailed seismic assessment.

- *Stage 6:* The site inspection is essential for confirming details unless the personnel who complete the bridge data sheets are confident that they know the structure well enough for such a visit to be unnecessary. A site visit by the specialist reviewer may also be necessary after Stage 7, if the reviewer identifies critical details that need clarification.

- *Stages 7 and 8:* The Specialist Review of the Bridges comprises a critical consideration of the bridges by a specialist bridge engineer who is conversant with the seismic behaviour of bridges. The purpose is to confirm that there is justification for the exclusion of the bridges that were excluded in Stage 3, and to familiarise the specialist with the structures for which a risk assessment is to be undertaken in Stage 9. The reviewer is also required to confirm (in Stage 8) the values allocated to the Seismic Attributes Grading procedure in Stage 5.

- *Stage 9:* The Risk Assessment comprises the identification and description of seismic "risk events" (possible failures or damage to various specific parts of the structure), assessment of their likelihood and the consequences arising from their occurrence, and determination of options and approximate costs of mitigation by retrofitting. This information is used to assess those bridges, or parts of bridges, that are most likely to return the greatest benefit from retrofitting, and hence to assist in deciding an order of priority of bridges that justify subsequent further detailed analysis. The economic ranking indicator (Stage 10) is also a key item that is used for this purpose. The risk assessment, which was developed on the basis of the risk management standard AS/NZS 4360:1995, is described in more detail below.

- *Stage 10:* The Economic Ranking Indicator is included in the procedures to take into account the comparative consequences and probabilities of loss of use of the bridges. It is derived by calculation using the most significant economic consequences that would be associated with the risk events identified in Stage 9. The indicator is based on key factors such as traffic volume, traffic disruption and other extra costs, and the estimated cost of retrofitting. The numerical value of the economic ranking indicator does not represent an actual benefit/cost ratio, which would be derived from a more detailed analysis, and is only for the purpose of assisting with the ranking of the bridges that are being assessed. The economic ranking indicator is described in more detail below.

- *Stage 11:* The Ranking for Further Analysis uses information gained from the SAG (Stage 8), the Risk Assessment (Stage 9), the Economic Ranking Indicator (Stage 10) and from other indicators to, firstly, rank the risk events for all the bridges being screened. A final list of bridges is then determined, in order of decreasing priority, that are judged to justify subsequent detailed assessment of their earthquake resistance. This list is the primary output from the screening procedure.

Risk Assessment

The risk assessment in Stage 9 comprises the following steps:

- *Identify Risk Events (Vulnerabilities to Seismic Damage):* Describe the location in the structure, and the nature of the risk event. There may be several risk events per bridge. Each is separately identified.

- *Estimate the Crossing Reinstatement Time for each Risk Event:* For each risk event estimate the number of days (D') for which the detour will have to be used until the crossing can be reopened with either a repaired or temporary crossing.

- *Carry out the Risk Analysis – (i) Likelihood:* For each risk event estimate the critical peak ground acceleration (PGA) that will cause the risk event. Decide the relevant seismic zone factor (Z) for the site. Determine the likelihood of the critical PGA occurring (a chart is provided to assist with this).

- *Carry out the Risk Analysis – (ii) Consequences:* For each risk event apply Table 1 to decide the consequences classification. For each risk event apply Table 2, using the values of D' (see definition above), the annual average daily traffic count on the bridge (AADT) and the extra distance travelled (EDT) when the detour is used. Take account of the effect on access to critical facilities.

- *Estimate the Level of Risk:* For each risk event apply the likelihood - consequences matrix in Table 3 to decide the level of risk associated with the risk event.

- *Evaluate the Risks:* Evaluate the risks, in general noting the risk events with a significant or high likelihood for further consideration. Generally a low or moderate level of risk should be considered to be acceptable and the associated risk event need not be considered further.

- *List the Treatment Options for the Risk Events:* For each risk event that was evaluated as having a significant or high likelihood, summarise the most suitable retrofit options for mitigating the risk. Estimate the rough order cost (ROC) for the retrofit, the number of days (D) required to reinstate the bridge to the existing traffic capacity, and the assessed journey speed (v_2) of traffic over the normal route with a temporary crossing or a reduced level of service.

- *Document the Information Derived from the Risk Analysis:* Record the information for each risk event.

It is intended that the risk assessment stage should be completed without significant analytical work being undertaken. For a screening procedure it is important to minimise the time spent, and the assessment therefore depends on experience and judgement of the assessors, rather than on detailed analysis and calculation.

Economic Ranking Indicator

The economic ranking indicator in Stage 10 is calculated for each risk event that has an unacceptable level of risk (i.e. generally a "significant" or "high" level). The calculation requires the determination of a number of parameters, as listed below, and is carried out in two stages to simplify the equations:

The Traffic Cost Parameter

The Traffic Cost Parameter (TCP) ($) = $D' \times AADT \times [0.35(d_1 - d_o) + a(d_1/v_1 - d_o/v_o)] + (D-D') \times AADT \times a(d_0/v_2 - d_0/v_0)$

where D = number of days to reinstate the bridge to the existing traffic capacity.

D' = number of days for which the detour will have to be used until the crossing can be reopened, with either a repaired or temporary crossing.

AADT = annual average daily traffic count on the bridge.

d_o = length of the normal route, between the detour connection points (km).

d_1 = length of the detour (km).

a = time parameter ($/hr), to be taken as 16 or 24, for urban or rural roads respectively.

v_0 = assessed journey speed of traffic over the normal route between the detour connection points under normal conditions (km/hr).

v_1 = assessed journey speed of traffic on the detour with diverted traffic (km/hr). If there are likely to be significant bottleneck effects on the detour, v_1 shall be reduced accordingly on the basis of judgement.

v_2 = assessed journey speed of traffic over the normal route, with a temporary crossing or a reduced level of service, between the detour connection points (km/hr).

The Economic Ranking Indicator

The Economic Ranking Indicator (ERI) = (PF x SLF x TCP) / (ROC)

where PF = probability factor from a table provided, using the PGA value determined for the risk assessment and the zone factor. The probability factor ranges between 0.07 and 0.21.

SLF = service life factor from a table provided. The service life factor ranges between 0.5 and 1.0 and applies to bridges expected to be replaced within the next 6 to 25 years or more, for whatever reason.

TCP = traffic cost parameter.

ROC = rough order cost of retrofit ($).

Discussion

Implementation of the screening procedure has generally reached Stage 6 in all regions (August 1999), but earlier pilot application of the procedure has resulted in completion of screening in two regions. The early stages are more routine than Stages 7 to 12, which require application of more judgement and understanding of structural performance in earthquakes, so it is too early to know how many problems and inconsistencies are likely to be encountered in the more complex stages.

Significant factors that affect the assessment are the site ground conditions and the susceptibility to liquefaction. Construction records of the older bridges do not often include detailed site investigation data and site investigation is generally too expensive to undertake just for screening purposes. Assessment of the site conditions in Stage 1 is therefore undertaken by experienced geotechnical specialists in order to justify eliminating as many eligible structures as possible from further assessment at an early stage.

The risk assessment (Stage 9) requires estimation, rather than calculation, of the peak ground acceleration that will cause the damaging risk event. Experience has shown that a tendency to conservative estimates at this stage results in a large percentage of bridges falling into the "significant" or "high" risk categories, with a consequent need to estimate the treatment options and calculate the economic risk indicators (Stage 10). Observations of damage in recent earthquakes has shown that, despite some well documented major bridge failures, a surprisingly low percentage of bridges sustain damage that will close highways for a significant time, even in regions of Modified Mercalli (MM) intensity IX. Short-term closure is often due to damage to the approaches, rather than to the structure. The screening manual [TNZ 1998] therefore contains some guidelines to relate the expected level of damage to general structures with MM values and peak ground acceleration.

SUMMARY AND CONCLUSIONS

This paper describes the seismic screening procedure that has been adopted for application to New Zealand's state highway bridges. The procedure was initially based on existing overseas systems, in which various bridge attributes were allocated "score" values. Pilot applications indicated that more emphasis on risk assessment and economic consequences was needed, and suitable procedures were developed and added. Introduction of the risk assessment and the economic ranking indicator (Stages 9 and 10) into the procedure has increased the confidence with which the results can be considered. The procedure is still subject to the application of much judgement but it is considered that, provided appropriately experienced personnel undertake the screening, they can be confident of economically producing a realistic list of priority bridges for subsequent detailed seismic assessment. At this stage of the project it is too early for decisions to be made on the extent of retrofitting that will actually be carried out on the stock of state highway bridges. This will ultimately depend on funding priorities based on risk considerations and economic factors.

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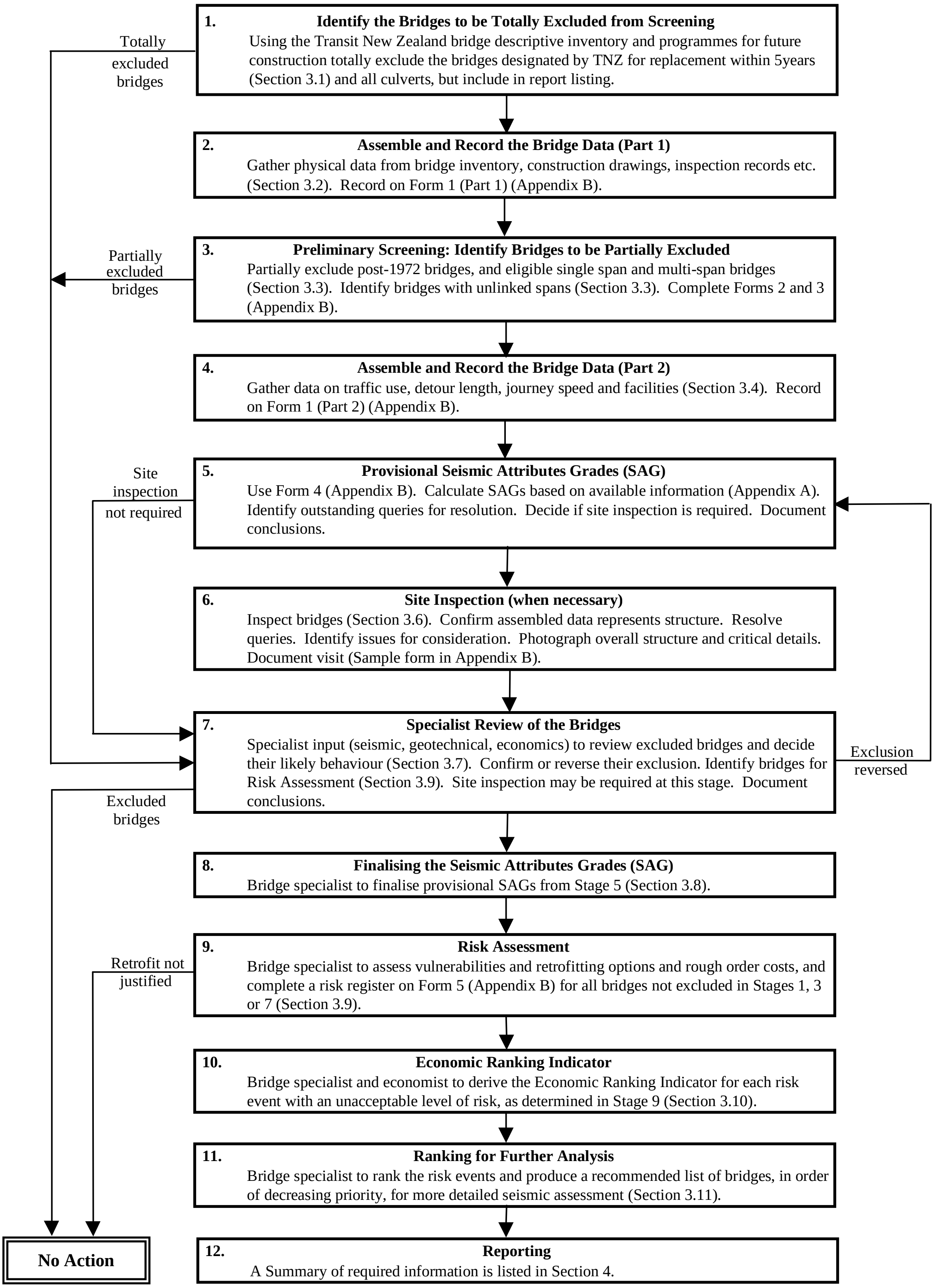
Figure 1 Bridge Seismic Screening Procedure



Note: Stages of work will normally be undertaken by the following personnel:

Stages 1 to 5	Engineering personnel familiar with the structures
Stage 6	Experienced bridge inspector or competent bridge designer
Stage 7 to 12	Bridge engineers, geotechnical engineers and economists experienced in the seismic aspects of bridges.

Table 1 Consequence Classifications Based on Bridge Damage and Safety

Extent of Damage to Bridge	Consequence Classification
Superficial damage, no disruption to traffic.	Insignificant
Significant damage to a single or two-span bridge requiring closure.	Minor
Significant damage in a number of locations on a bridge of more than two spans requiring closure.	Moderate
Damage requiring replacement of a single span.	Major
Damage requiring replacement of more than one span.	Catastrophic

Table 2 Consequence Classifications Based on Traffic Disruption and Lifelines

Extent of Traffic Disruption	Consequence Classification
$D' \times AADT \times EDT \leq 10^4$	Insignificant
$10^4 < D' \times AADT \times EDT \leq 10^5$	Minor
$10^5 < D' \times AADT \times EDT \leq 10^6$	Moderate
$10^6 < D' \times AADT \times EDT \leq 10^7$	Major
$D' \times AADT \times EDT > 10^7$	Catastrophic

Where:

D' = number of days for which the detour will have to be used until the crossing can be reopened with either a repaired or temporary crossing.

AADT = annual average daily traffic count on the bridge.

EDT = "Extra distance travelled" (difference between detour length and normal route length).

When assessing the consequences of traffic disruption, routes to critical facilities that are likely to be required for emergency relief operations following an earthquake, such as hospitals, airports and rail and harbour terminals, shall be given special consideration and the consequences classification adjusted accordingly.

Table 3 Likelihood – Consequence Matrix for Estimating Level of Risk

Likelihood	Consequences				
	Insignificant	Minor	Moderate	Major	Catastrophic
Very Likely	Significant	Significant	High	High	High
Likely	Moderate	Significant	Significant	High	High
Moderate	Low	Moderate	Significant	High	High
Unlikely	Low	Low	Moderate	Significant	High
Very Unlikely	Low	Low	Moderate	Significant	Significant