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SEISMIC ANALYSIS AND DYNAMIC TESTING OF A SPILLWAY RADIAL GATE

Wendy E DANIELL[1] And Colin A TAYLOR[2]

SUMMARY

The radial flood gate at Kilmorack Dam in Scotland was evaluated for seismic loading. The study included dynamic hammer testing of the prototype gate, the seismic response analysis of a three-dimensional model of the gate and the equivalent-static analysis of simple two-dimensional models. Natural frequencies and mode shapes from the tests were employed for validating the three-dimensional finite element model of the gate. The time history analysis of the three-dimensional model indicated that this and similar gates may be vulnerable to UK earthquakes. The equivalent-static analysis of 2-D models was compared with the dynamic three-dimensional analysis to establish the suitability of the equivalent-static method for the seismic assessment of other similar gates. The equivalent static analysis of 2-D models was shown to be appropriate for preliminary assessments, and the dynamic analysis of 3-D models appropriate for detailed analysis where required.

INTRODUCTION

The dynamic testing and seismic analysis of the radial gate at Kilmorack Dam were conducted as part of a programme investigating the seismic safety of structures appurtenant to dams. The gate, which was not designed for earthquakes, is typical for dam sites owned by Scottish and Southern Energy, the largest hydro-power generator in the UK. Constructed in steel, it is 7.9 metres wide and 8.2 metres high, and comprises a skin-plate stiffened by vertical ribs and horizontal cross-girders, supported by radial struts extending back to pivot bearings anchored into the dam.

The aims of the study were, to establish the vulnerability of the gate to UK earthquakes by measuring its dynamic characteristics, and to determine a suitable method for the seismic analysis of the gate. Then, the conclusions from the study could then be applied to other similar gates.

Dynamic tests were conducted on the gate using an instrumented 6 kg hammer. Modal properties were measured and used for the validation of a 3-D (three-dimensional) FE (finite element) model of the gate for its seismic response analysis. The results of the dynamic 3-D FE analysis were compared with those from an equivalent-static analysis of simple 2-D models of the gate to assess whether the simple analytical method is adequate for the seismic assessment of typical UK gates.

HAMMER TESTS

The hammer tests were conducted, over a period of four days, as a preliminary investigation into the dynamic characteristics of the gate. A full modal survey was not intended, only the identification of prominent modes of vibration. It was expected that a mildly non-linear response of the gate would be observed due to the behaviour of the rubber seals at the sides of the gate and the slip-stick action that may occur along the sill and in the pivot bearings.

Equipment and Test Method

A 6 Kg sledgehammer instrumented with a piezoelectric force transducer was used for the forced excitation of the gate. The response of the gate was measured using four Sundstrand Q-Flex type QA-700 accelerometers with nominal sensitivity of 20 Volts/g. Both force and response signals were filtered using a 16th order low-

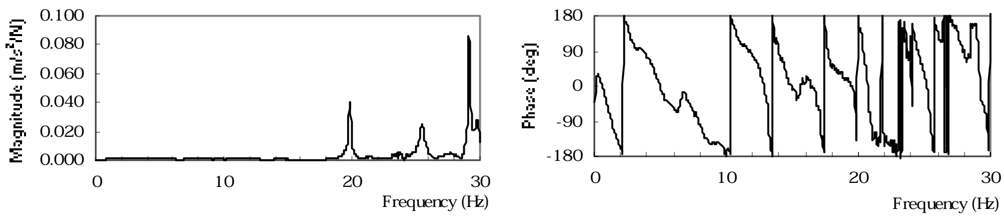
[1] *Research Fellow, University of Bristol*
[2] *Reader, University of Bristol*

pass Butterworth filter with a cut-off frequency of 30 Hz. Accelerometers mounted on steel blocks were attached to the gate with small rare-earth magnets. Force and response signals were monitored on an oscilloscope and analysed directly using an Advantest R9211C FFT Servo Analyser.

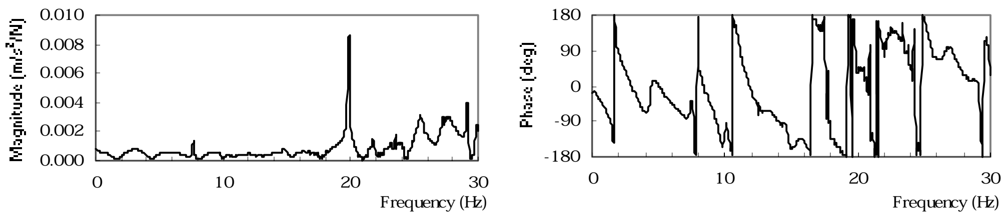
The gate was tested in its closed position with the water level 0.54 metres below the top of the gate. For safety reasons, rope access contractors were employed to place accelerometers and to excite the gate with the hammer. They abseiled from the crest of the dam onto the gate. Hammer excitation was concentrated on the upper cross-girder, as it was almost level, and, therefore, easy to balance on. Continuous hammer hitting is fatiguing work, so the hammer was swung low, below shoulder level, to hit the top cross-girder, rather than above shoulder level where the stiffened-plate could have been excited. The gate was excited in the stream and the cross-stream directions, and accelerations were measured around the upper radial struts and the upper cross-girder (henceforth referred to as the upper frame). In the stream direction, the cross-girder was hit off-centre to excite as many modes of vibration as possible.

Analysis of Data

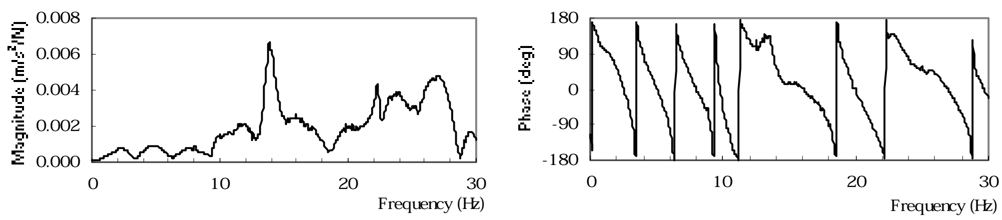
During the tests, the Advantest spectrum analyser was employed to calculate FRF (frequency response function) spectra, relating responses to their excitation force. The FRF for each location was obtained from an average of ten hammer blows for a spectral resolution of 0.0625 Hz. Measured FRF were stored on magnetic diskettes for later modal analysis.



(a) FRF spectra measured on upper radial strut for stream-direction excitation



(b) FRF spectra measured on upper cross-girder for stream-direction excitation



(c) FRF spectra measured on upper cross-girder for cross-stream excitation

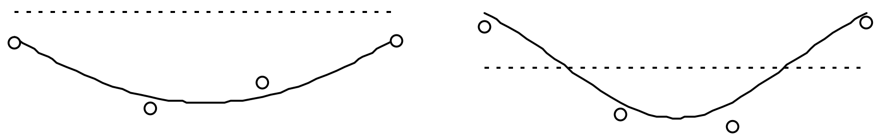
Figure 1: Typical FRF Spectra Measured from Hammer Tests

Typical FRF spectra (Figure 1) are presented showing their magnitude and phase components. Coherence spectra were acquired too, but they have not been presented. Modal peaks in the spectra indicate the presence of a number of modes of vibration below 30 Hz. The well-defined peaks represent individual modes, and their repeatability across the full spectral set made their modal analysis relatively straightforward. The broader, flatter peaks were less repeatable with their natural frequencies shifting. They may have been caused by either a number of close overlapping modal peaks or by non-linear behaviour of the boundary conditions to the gate.

The measured FRF spectra were not adequate for a full modal analysis. For that, further testing would be required exciting the gate at different locations, so that individual modes could be identified more easily, and measuring responses over the whole gate. However, some modes of vibration were identified from single-degree-of-freedom curve fitting to the prominent modal peaks in the magnitude component of the FRF spectra. Natural frequencies, modal damping factors and modal residues were estimated, and phase differences between the responses and the force were obtained from the phase component of the FRF.

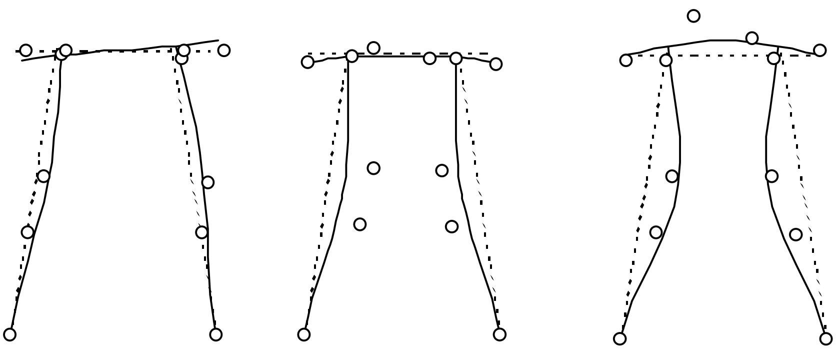
Results

Some of the measured mode shapes are shown in Figure 2 and their estimated modal damping factors and measured coherence are given in Table 1. Components of the mode shapes are shown for the upper frame and the top of the stiffened plate. All mode shapes demonstrated movement at the sides of the stiffened-plate. Although, a cross-stream sway mode was identified at 14.0 Hz, the FRF spectra indicated that other sway modes existed at lower frequencies. For example, a definite peak occurred at 10 Hz in some spectra and broad low peaks occurred at approximately 2.5 Hz, 4.5 Hz and 7.5 Hz (Figure 1c). However, the associated mode shapes could not be identified due to poor clarity and lack of repeatability of modal peaks. Also, the associated coherence values fell below 0.8 Hz indicating poorer quality measurements for these modes. The poor definition of cross-stream modes resulted probably from non-linear behaviour of the side seals to the gate.



Tests 7.4 Hz (Model 6.3 Hz) **Tests 14.6 Hz (Model 13.6 Hz)**

(a) Mode shapes at top of stiffened plate



Tests 14.0 Hz (Model 13.9 Hz) **Tests 19.8 Hz (Model 18.9 Hz)** **Tests 25.5 Hz (Model 22.8 Hz)**

○ **Test measurements** ——— **Finite element model**

Mode shapes on upper frame

Figure 2: Modes Shapes from Hammer Tests and Three-Dimensional Finite Element Model

Table 1

Frequency (Hz)	Description of Mode	Modal Damping (%)	Coherence
7.4	1st bending mode of upper cantilevered portion of plate	0.8	0.79-0.89
14.0	sway mode of gate	1.9-3.0	0.94-0.98
14.6	2nd symmetric bending mode of cantilevered portion of plate	1.0	0.96-0.97
19.7-19.9	bending mode of upper frame	0.17-0.37	0.90-0.98
25.4- 25.6	bending and axial mode of upper frame	0.31-1.10	0.97-0.99

DEVELOPMENT AND VALIDATION OF 3-D FINITE ELEMENT MODEL

Description of Model

The FE model of the gate is shown in Figure 3. For the steel, the modulus of elasticity was taken as 210 GPa, the density as 7850 kg/m3 and Poisson's ratio as 0.3.

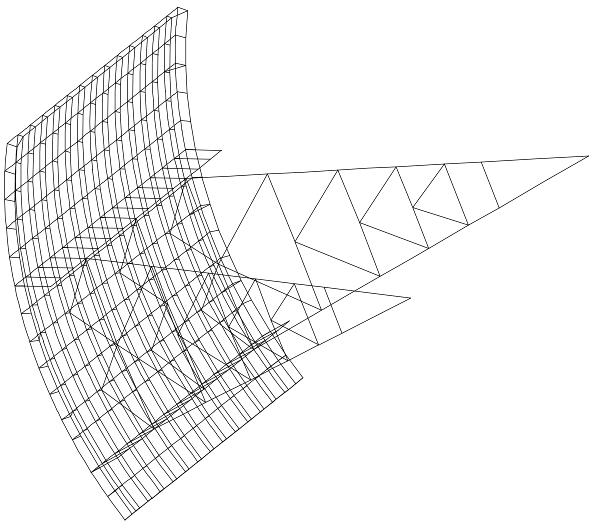


Figure 3: Three-Dimensional Finite Element Model of Gate

The skin-plate was modelled with a total of 196 sixteen-noded, rectangular, shell elements and, the vertical stiffeners and cross-girders with two-noded beam elements. The beam nodes corresponded to the corner nodes of the shell elements, and they were joined by rigid links, thereby modelling composite action of the plate with the stiffeners and the cross-girders. Cubic polynomial displacement solutions for the shell and the beam elements ensured compatibility of displacements. All members of the radial arms were modelled with two-noded beam elements, assuming full fixity at all joints.

At the pivot bearing, all translational and rotational degrees of freedom were assumed to be fully restrained. Clearly, the gate can rotate around the bearings, and drawings of the gate indicated that cross-stream movement up to 9.5 mm could occur in the bearings due to the hubs sliding along their axles. However, rotation around the axes of the bearings and cross-stream sliding was not permitted, as it was assumed that the small forces experienced during hammer testing would not have been sufficient to overcome any frictional resistance.

Three different boundary conditions, A, B and C (Table 2) were considered at the sides and the sill of the stiffened plate. For boundary condition A, the sides of the gate were modelled as free, and sliding along the sill was permitted. The fixed restraint tangential to the curvature of the plate represented the effect of gravity holding the gate closed. For boundary conditions B and C, the rubber sides seals were modelled as spring elements. An equivalent stiffness was estimated accounting for the material properties of the rubber seal (Schmausser and Hartl, 1988). For boundary condition C, sliding at the gate sill was restrained, assuming that any friction would not have been overcome during hammer testing.

Table 2

Boundary Condition	Sides of Stiffened Plate	Gate Sill
A	free	translational DOF tangential to plate fixed
B	springs	translational DOF tangential to plate fixed
C	springs	all translational DOFs fixed

Note: DOF represents degree-of-freedom

The dynamic interaction between the gate and the reservoir was approximated using the added mass concept. The hydrodynamic mass was calculated using Kolkman's method (1988) developed specifically for hydraulic gates of any configuration. The method solves the two-dimensional potential flow problem using finite differences and the Gauss-Seidel iteration method, and it can be implemented on a spreadsheet. The reservoir is modelled as a square mesh with appropriate boundary conditions. For comparison with the hammer tests, the boundary conditions to the reservoir modelled only the gate moving. The added mass was computed as 269 tonnes compared to the gate's mass of 18 tonnes. It was represented in the FE model as concentrated masses using mass elements placed at the corner nodes of the shell elements, active only along axes radial to the curvature of the plate.

Modal Analyses

Table 3

Description of Mode	Dry Gate	Gate with Hydrodynamic Mass for Hammer Test Conditions		
	Boundary Condition A	Boundary Condition A	Boundary Condition B	Boundary Condition C
1st cross-stream sway mode	3.0	2.4 (1st Mode)	7.3 (1st Mode)	8.6 (4th Mode)
1st symmetric mode of cantilever plate	15.3	6.0 (2nd Mode)	6.2 (2nd Mode)	6.3 (1st Mode)
1st anti-symmetric mode of cantilever plate	17.6	7.0 (3rd Mode)	8.2 (4th Mode)	8.3 (2nd Mode)
1st bending mode of central area of plate	39.7	8.1 (4th Mode)	8.1 (3rd Mode)	8.4 (3rd Mode)
2nd symmetric bending of cantilever plate	29.1	12.3	12.8	13.6

Modal analyses were run for the model of the dry gate (i.e. without the hydrodynamic mass), for boundary condition A, and for models of the gate with the hydrodynamic mass for boundary conditions A, B and C. Modes in the frequency range 0-30 Hz were of interest for comparison with the hammer tests. Computed natural frequencies for selected modes are given in Table 2. For the dry gate, there were eight modes below 30 Hz. Generally, mode shapes showed permutations of bending modes of the stiffened plate combined with bending modes of the radial struts. When the hydrodynamic mass was added to the model, natural frequencies were reduced significantly, increasing the number of modes below 30 Hz to fifty-three. The addition of springs at the sides of the gate (boundary condition B) made little difference to the modal properties, excepting the first cross-stream mode whose frequency increased from 2.4 to 7.3 Hz. The introduction of the additional restraints at the gate sill (boundary condition C) reduced the number of modes below 30 Hz to forty-five. Natural frequencies of the cross-stream modes increased noticeably, and there were slight increases in the frequencies of other modes.

Comparison with Hammer Tests

Clear correlation between the measured and the theoretical modes was difficult to achieve, as only a few modes of vibration, measured at limited locations, were identified from the tests. The presence of a number of close modes below 30 Hz was demonstrated from the tests and the FE models. Many of the theoretical mode shapes appeared similar especially when viewed only around the upper frame, which is where the corresponding test measurements were made. Thus, it was difficult to find an exact match with the measured modes.

However, a fair correlation was achieved for some modes. Considering the non-linear boundary conditions of the gate, relatively good matches were found for the first and second symmetric mode shapes of the upper cantilevered portion of the stiffened plate and for the modes of the gate measured at 19.8 and 25.5 Hz (Figure 3). The model with boundary condition C provided the best correlation, producing a match for the sway mode measured at 14 Hz (Figure 2). Measurements on the upper cross-girder for this mode were made in the cross-stream direction only, explaining the poor correlation along the girder. Generally, the natural frequencies of the theoretical modes were lower than the corresponding measured modes, indicating either that the added hydrodynamic mass had been overestimated or that the effective stiffness of the model had been underestimated.

The lowest stream-direction modes from all models included the first symmetric and anti-symmetric modes for the upper cantilevered portion of the stiffened plate and the first bending mode of the central portion of the stiffened plate (Table 3). All of these modes displayed significant displacements at the top of the plate, and for all models; their natural frequencies fell within a 2 Hz band. Close inspection of the spectra measured at the top of the plate (Figure 4) indicated that there might be three modes of vibration in the range 7.4 to 7.9 Hz, corresponding with the FE results. However, for confirmation, further tests are required with direct excitation of the stiffened plate at appropriate locations.

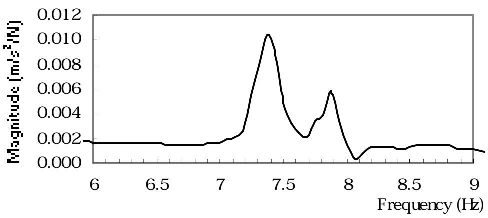


Figure 4: FRF Spectrum Measured on Top of Stiffened Plate for Stream-Direction Excitation

In the FE models, numerous modes below 30 Hz occur as a result of bending modes of the plate combining with bending modes of the radial arms in many permutations. Correspondingly, the measured FRF indicated the presence of a number of close modes. Overall, the evidence indicated that the FE model was valid for a dynamic analysis of the radial gate. To increase confidence in its validity, further testing would be required to identify more modes of vibration in more detail for improved correlation with the theoretical model.

SEISMIC ANALYSES OF KILMORACK GATE

The gate was analysed in its closed position, as that is its normal operating condition. There was no seismic analysis of the opened gate corresponding to the flood condition, as the probability of the simultaneous occurrence of a large earthquake and flooding are very low. The gate was analysed for a peak ground acceleration of 0.24g corresponding to a 1 in 10,000 year earthquake at the site. Only horizontal components of the earthquake were considered in the analysis and hydrostatic and gravity loading were included. In the absence of any guidelines, the same return period of 10,000 years was adopted for the analysis of the gate, as used for the Safety Evaluation Earthquake for the dam. The suitability of such an extreme event for the analysis of gates is a subject of ongoing debate.

Dynamic Analysis of 3-D Model

The 3-D FE model was modified for the seismic analysis. Boundary conditions were adjusted to account for the effect of the larger earthquake forces. The rotational DOF around the axis of the pivot bearing was released, and boundary condition A (Table 2) was applied at the sides and the sill of the gate. Kolkman's added mass was re-evaluated as 435 tonnes for the seismic condition with both the dam and gate moving as boundary conditions to the reservoir. The increased hydrodynamic mass resulted in a significant reduction in the natural frequencies of vibration for the gate.

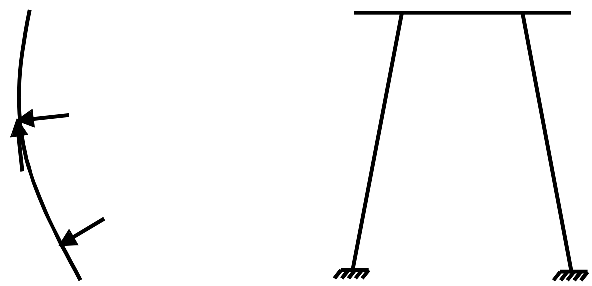
Modal participation factors for earthquake loading were calculated. They showed that the seismic response of the gate for stream direction loading would be dominated by the first symmetric cantilever plate mode, at 4.1 Hz, and the first bending mode of the central portion of the stiffened plate, at 6.4 Hz. Under cross-stream loading, the seismic response would be dominated by the fundamental sway mode at 2.1 Hz.

Time history analyses were run for individual earthquake components and for combined static and seismic loading. A rigid body response of the dam was assumed, so a standard UK response spectrum formed the basis of the seismic input to the gate from which artificial accelerograms were generated for the time history analyses. 5% damping was employed based on USCOLD (1995) recommendations.

Under the combined load, the effective load on the gate during the earthquake increased by about 85% compared to the static case, subjecting the gate to a load almost twice that for which it was designed. This result suggests that this and similar non-seismically designed gates may be vulnerable to earthquakes.

The analysis of the 3-D model highlighted the arching action of the stiffened plate causing bending around the minor axes of the cross-girders. Although the bending moments were small, the resulting stresses were significant due to the slender nature of the cross-girders.

Equivalent-Static Analysis of Simple 2-D Models



(a) **(b)**

Figure 5: Simple two-dimensional models for equivalent-static analysis

Simple 2-D models for the gate represented the stiffened plate as a simply supported continuous beam (Figure 5a) and the upper and lower frames as portal frames (Figure 5b) with the hydrodynamic and the gate's mass apportioned appropriately. Seismic forces were represented as equivalent-static forces calculated by multiplying the total effective mass of the gate by the peak acceleration of the input response spectrum, although, ASCE Standard 4-86 (1986) recommends multiplying the peak acceleration by 1.5 for multi-degree-of-freedom models to account for multi-mode effects.

Comparison of Analytical Methods

The dynamic and equivalent-static analyses generated similar results for the effective seismic load on the gate. For stream-direction seismic loading only, reactions at the bearings were 1450 kN from the equivalent-static analysis, 26% higher than the maximum reaction of 1155 kN from the 3-D dynamic analyses. However, the equivalent-static analysis yielded axial forces in the radial struts up to 34% higher for the upper struts, but within 10% either way for the lower struts, compared to the dynamic analysis. For cross-stream seismic loading, the equivalent-static analysis gave significantly higher bending moments due to use of the peak acceleration of the input response spectrum which is 2.7 times the response spectrum acceleration corresponding to the natural frequency for the dominant sway mode at 2.1 Hz.

Forces and moments in the cross-girders could not be compared directly, as composite action with the skin-plate was represented in the 3-D model but not in the 2-D models. A simple comparison was made by combining the direct stresses at the extreme fibres of the cross-girders due to the axial force and bending around the major axis. The equivalent-static analysis produced higher stresses, but bending around the minor axis was not included in the comparison.

Generally, the equivalent-static analysis yielded higher responses, although axial forces in the lower radial struts were underestimated slightly, and the significant 3-D effects due to arching of the stiffened plate could not be represented. Given these limitations, the equivalent-static analysis of simple 2-D models appears to be appropriate for preliminary seismic assessments. If further more detailed analysis is required, then dynamic analysis of a 3-D model is appropriate for the main seismic evaluation.

CONCLUSIONS

Preliminary dynamic hammer tests on the radial gate at Kilmorack Dam demonstrated that the dynamic behaviour of this type of gate is complicated. The gate exhibited many modes of vibration in the frequency range of interest for earthquake analysis. The modal analysis of the corresponding 3-D FE model indicated that they occur as a result of many permutations of plate bending modes combining with bending modes of the radial struts. In addition, the quality of the test data indicated that non-linear boundary conditions existed at the sides and sill of the gate and at its pivot bearings. Further more detailed tests are required for a full investigation of the gates dynamic characteristics.

Mode shapes were identified from the tests and they correlated reasonably with theoretical modes from the 3-D FE model, thus validating the model for seismic analysis.

The seismic analysis of the 3-D model demonstrated that the effective load on the gate during the 1 in 10,000 year earthquake at the site would be almost double that for the hydrostatic condition, indicating that this, and other similar non-seismically designed gates, may be vulnerable to the more extreme earthquakes likely to be experienced in the UK.

The time history response analysis of the 3-D FE model was compared with the equivalent-static analysis of simple 2-D models. It was demonstrated that the equivalent-static analysis is adequate for preliminary assessments, as the 2-D models can not account for 3-D effects in the gate, while the dynamic analysis of 3-D models is more appropriate for the main seismic evaluation of a radial gate.

ACKNOWLEDGEMENTS

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