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MODELLING OF THE FULL-RANGE RESPONSE OF ABUTMENT-BACKFILL SYSTEMS

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Abstract

Over the last decades, the findings of numerous analytical studies, experiments and in-situ observations have highlighted the importance of the deck-abutment-backfill interaction on the seismic response of bridges. These findings have allowed various research groups to develop closed-form relationships that describe the nonlinear behaviour of the abutment-backfill system. Such relationships have been broadly used in research, reflected in modern seismic codes and guidelines, and incorporated in nonlinear analysis software.

However, the behaviour of the abutment-backfill systems after the attainment of peak strength has been neither studied to a sufficient extent from the analysis point of view nor included in the constitutive models of widely used nonlinear analysis software packages, such as OpenSees, even though large-scale tests have captured this critical phase of the response. The softening region of the response of the backfill has been addressed by some hardening/softening plasticity models that are not appropriate when simpler approaches (like Winkler springs) are used. Notably, the estimation of the abutment-backfill response at any level of seismic intensity is necessary for an appropriate fragility analysis of a bridge since the abutment-backfill component is almost always considered to affect at least some aspects of the bridge response and its failure is one of the possible failure modes that should be accounted for.

In the above context, the main aim of the work presented herein is to propose an extended version of the 'Hyperbolic Gap' OpenSees material, the so-called 'Hyperbolic Gap Softening' material, which allows the user to define a set of parameters that describe the softening branch of the backbone curve of an abutment-backfill system. In addition to tests of the new model using a simple configuration, results of response history analyses of a case study bridge with different abutment-backfill properties are also reported, with a view to verifying the applicability of the proposed model and investigating the importance of capturing the post-peak abutment-backfill behaviour on the estimation of the response of a bridge.

Keywords: Hyperbolic gap, softening, OpenSees, post-peak response, abutment, backfill

1 INTRODUCTION

A large number of studies have been devoted to a better understanding of the behaviour of the abutment-backfill system in the longitudinal direction of the bridges, including full- and small-scale experiments of model walls and pile caps supporting backfill soil and analytical studies [1]. Most of these studies attempted to develop representative equivalent linear, bilinear, or other nonlinear estimations of the abutment-backfill lateral force (F) as a function of lateral displacement (δ) that could be implemented in elastic, nonlinear static or nonlinear dynamic (response history) analyses of finite element models in the form of soil springs. One of the first proposed models was that in [2], a simplified model composed of bilinear springs and dashpots to study the response of skew bridges, while [3] used an approach based on the classical Rankine theory [4] to estimate the equivalent stiffness of a seat-type abutment-backfill system in the longitudinal direction that was incorporated in the finite element model of the bridge in the form of a vertical Winkler beam. The remarkable progress in nonlinear analysis methods that was marked in the years that followed, turned the research focus to the development of fully nonlinear models that were able to capture the behaviour of the abutment-backfill system more accurately, usually based on experimental results. Among the best known models of this category is that of Shamsabadi et al. ([1], [5]), who developed the 'Log-Spiral Hyperbolic' (LSH) stress-strain model by adopting a log-spiral passive failure surface in the backfill soil and coupling it with the hyperbolic stress-strain law proposed in [6]. Their model was validated against the results of large- and small-scale tests. Extending the LSH model, the same research group proposed several more practice-oriented, closed-form force-displacement relationships accounting for the dependence on the backwall height (Extended Hyperbolic Force-Displacement model or EHFD, [7]) and covering a broad range of cohesion values, friction angles and wall-soil interface friction angles (Generalized Hyperbolic Force-Displacement model or GHFD, [8]), being more appropriate to represent the various backfill soil types used in bridge construction. The development of these models focused solely on the behaviour of the so-called 'sacrificial' backwalls, i.e., backwalls that are assumed to shear off during a seismic event right after the collision with the deck to protect the substructure, as recommended by the Caltrans design guidelines [9]. However, lots of backwalls worldwide are stronger and have a more ductile behaviour, forming a plastic hinge at their bottom as they collide with the deck. Such behaviour is common in the seismic regions of Europe [10], [11] and also in bridges in seismic regions of the US that were designed before the implementation of the Caltrans guidelines [12]. Therefore, modelling methods that include nonlinear beam-column elements and soil springs to represent the structural parts of the abutment and the backfill soil, respectively, have been proposed (e.g. [10], [13]), while [14] developed a methodology that results in a simple single-spring model that is able to capture effectively the nonlinear behaviour of the entire abutment-backfill system with 'hinging' backwall.

Based on the hyperbolic relationship in [15] and the LSH model ([1], [5]), the 'Hyperbolic Gap Material' force-displacement model was developed by Dryden & Fenves [16] and was implemented in OpenSees [17]. Since its development, the 'Hyperbolic Gap Material' has been used widely in research works that consider the nonlinearity of the abutment-backfill system and its contribution to the dynamic response of bridges (e.g., [18]–[22]). This is a compression-only constitutive model that follows a hyperbolic backbone curve, which has been shown to properly capture the actual backfill soil behaviour found in experimental campaigns like [23]; it includes an initial zero-valued branch to represent the gap between the deck and the backwall allowing the user to avoid the implementation of separate gap elements, which are known to be prone to numerical difficulties (e.g. [14], [24]) and it is also able to capture the accumulated damage in the backfill soil. However, it has a number of drawbacks, the most important arguably being that it does not offer the option of defining a post-peak softening behaviour, although this behaviour has been observed in pertinent tests (e.g. [25]–[27]) and hence, it may result in inaccuracies in the representation of the post-peak abutment-backfill behaviour in the case of ground motions of high intensity. These inaccuracies are important when the full-range response of the abutment-backfill system has to be taken into account, which is notably the case in vulnerability/fragility analysis.

The main aim of this paper is to present a new, improved version of the 'Hyperbolic Gap Material', the so-called 'Hyperbolic Gap Softening' model that was developed by the authors in the form of a new 'object' of the 'Uniaxial Material' class in OpenSees. The 'Hyperbolic Gap Softening' model allows the user to define a post-peak descending branch and a subsequent residual force branch to fully cover the response of the abutment-backfill system, according to available experimental results. In addition to tests of the new model using a simple configuration, indicative results are also shown of nonlinear response history analyses of a 3D bridge model that were conducted to verify the applicability of the new model and to compare its effect on the bridge response with that of the 'Hyperbolic Gap Material'.

2 FORMULATION OF THE PROPOSED MODEL

The compression-only backbone curve of the existing 'Hyperbolic Gap Material' model is described by Equation 1:

$$F(x) = \frac{x}{\frac{1}{K_{max}} + R_f \frac{x}{F_{ult}}} \tag{1}$$

where F(x) is the lateral force that develops at the backfill, x is the horizontal displacement, while the user-defined parameters are K_{max}, the initial stiffness of the backfill soil, which is the initial slope of the force – displacement curve, F_{ult}, the 'ultimate' passive resistance, and R_f, the 'failure ratio', i.e., the ratio of F_{ult} to the strength corresponding to the asymptote of the hyperbola (eq. 1). The cyclic behaviour of the model is determined by K_{ur}, the stiffness during unloading and reloading, also defined by the user. As commented in [27], Equation 1 is meant to represent the passive force-displacement behaviour up to peak resistance and some sort of capping of the derived curve should be implemented if the behaviour beyond that point needs to be considered. The reason for this limitation is that in Equation 1 there is no displacement related to a maximum resistance value; hence, the resulting backbone curve extrapolates to infinity in terms of x as the corresponding F(x) tends to the asymptote of the hyperbola. An indicative example of the 'Hyperbolic Gap Material' presented in [28] is shown in Figure 1.

As already stated, the model proposed herein was mainly developed to offer the option of modelling the post-peak behaviour of the backfill soil in an effective, yet reasonably accurate, way, based on past research works that studied this behaviour. The results collected by field observations and the literature review of [26] showed that after reaching its peak, the passive resistance of a backfill drops until a level of residual passive force (F_{res}), which is about 60% to 70% of the maximum passive force F_{ult}, at a displacement x_{res} that is approximately equal to 2.5 to 3 times the value of displacement at maximum passive force (x_{max}). The shape of the descending branch often resembles an exponential curve with an inflection point at about $2x_{max}$ according to [26]. However, the shape of the descending branch varies significantly in tests with different backfill soil materials and it depends on various parameters, such as the cohesion and the water content [26], [27]. The inflection point of the descending branch is also case-dependent. For instance, although the test results of [27] for soil confirm the assumption of [26] regarding the point of inflection of the descending branch, the results of the same study for soil with higher water content indicate that there is no evident inflection before the onset of the branch of the residual force (Figure 2).

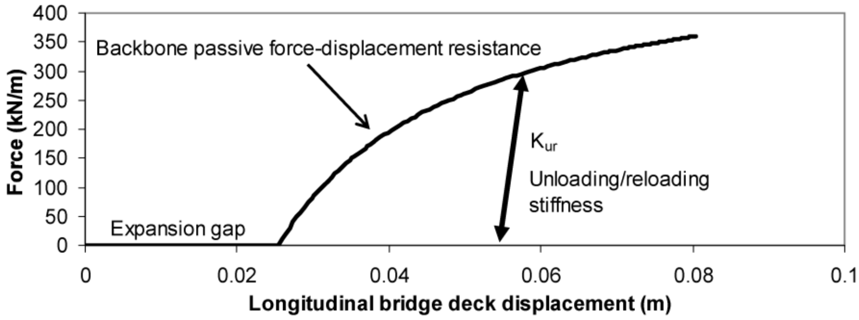


Figure 1. Force-displacement behaviour of the 'Hyperbolic Gap Material' [28]

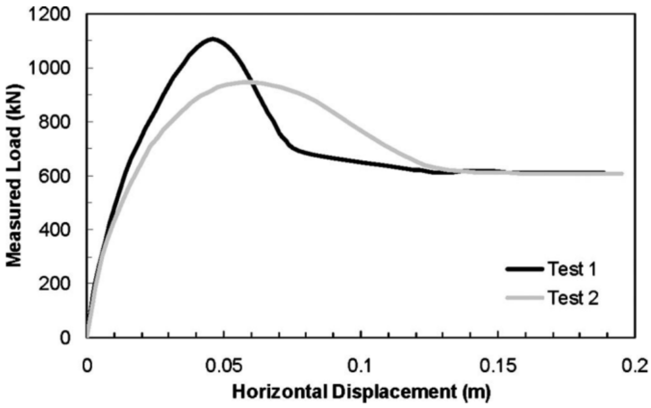


Figure 2. Experimentally derived force-displacement backbone relationships of engineered silty sand backfill. Test 1: Dry conditions. Test 2: Field water conditions [27]

Another ambiguous point in the formulation of the 'Hyperbolic Gap Material' is the use of the empirically defined R_f parameter (Equation 1), whose value may vary significantly from case to case. For instance, [6] suggest a value range of 0.75 – 0.95, while [29] fitted their experimental results to Equation 1 with $R_f = 0.7$. The fact that other research works introduced modified versions of Equation 1 resulting in a different range of empirically defined R_f values (e.g., Shamsabadi et al. [1] recommend values from 0.94 to 0.98 for their closed-form relationship) may also cause confusion. Moreover, R_f does not have any direct physical meaning, while its accurate estimation is impossible without calibration against available test data, which are not always available. On the contrary, x_{max} (the displacement at F_{ult}) has a clear physical meaning and it is also relevant in the assessment of the abutment-backfill performance since it defines a limit state of the abutment-backfill system. Furthermore, there are recommended x_{max} values available in the literature (e.g., [1], [8], [26]) based on experiments with various backfill soil types. Therefore, it was decided to select x_{max} instead of R_f as an input parameter of the new 'Hyperbolic Gap Softening' OpenSees material. To this purpose, R_f was expressed as a function of K_{max}, F_{ult} and x_{max} by solving Equation 1 for R_f taking $x = x_{max}$ and $F(x) = F(x_{max}) = F_{ult}$:

$$R_f = 1 - \frac{F_{ult}}{K_{max}\, x_{max}} \tag{2}$$

In the light of the previous considerations, a simplified bilinear form was selected for the post-peak part of the backbone curve of the new 'Hyperbolic Gap Softening' material object of OpenSees. The two branches of this bilinear segment represent the softening and the residual force phases of the backfill. The 'Hyperbolic Gap Softening' model allows the user to select the values of the parameters that define these two new branches, in order to approximate the softening behaviour of a backfill with an acceptable level of accuracy. Namely, these parameters are 1) the displacement at F_{ult}, considering a closed gap between the deck and the backwall (x_{max}), 2) the displacement at the onset of the residual force branch of the backbone (x_{res}), and 3) the value of the residual force (F_{res}). The backbone of the 'Hyperbolic Gap Material' (Equation 1) was adopted as the behaviour of the new model up to the point of maximum passive force, while the way that the unloading/reloading stiffness K_{ur} is defined was also kept the same. The sign conventions of the 'Hyperbolic Gap Material' were followed in the 'Hyperbolic Gap Softening', since it is also a compression-only model, and the signs of the newly introduced parameters were set accordingly. All user-defined input parameters, including those that were adopted from the 'Hyperbolic Gap Material', are summarised in Table 1. A typical backbone curve of the 'Hyperbolic Gap Softening' model is illustrated in Figure 3.

Input parameter	*Description*
K_{max}	Initial stiffness
K_{ur}	Unloading/reloading stiffness
x_{max}	Displacement at F_{ult} (with closed gap)
F_{ult}	Maximum passive resistance
x_{gap}	Initial gap
x_{res}	Displacement at the onset of the residual force branch
F_{res}	Residual passive resistance

Table 1: User defined input parameters of the 'Hyperbolic Gap Softening' OpenSees material

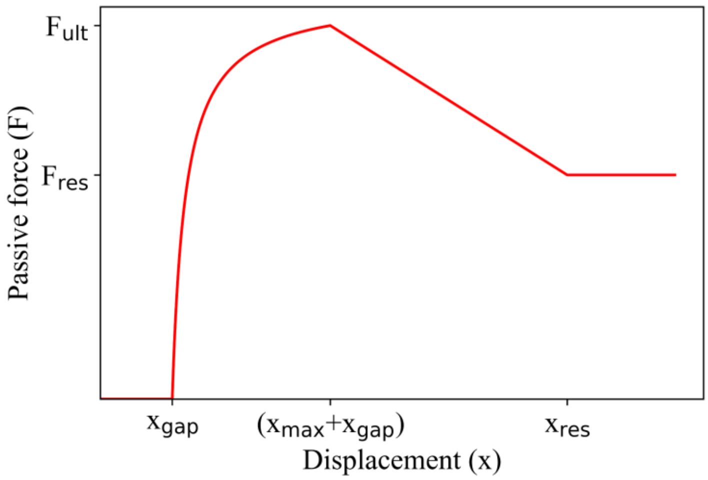


Figure 3. Typical backbone curve of the 'Hyperbolic Gap Softening' OpenSees material

Apart from the introduction of the softening and the residual force branches, the overshooting issues of the 'Hyperbolic Gap Material' that were noted occasionally in the reloading phase by the authors during their research (e.g. Figure 4a) were fixed in the 'Hyperbolic Gap Softening' material (Figure 4b). In the new material, the force is not allowed to exceed the backbone curve at any point. Whenever such an exceedance occurs at an iteration of an analysis time step, the overshooting force is added to the residual force of the associated finite element (typically a uniaxial ‘zero-length’ element).

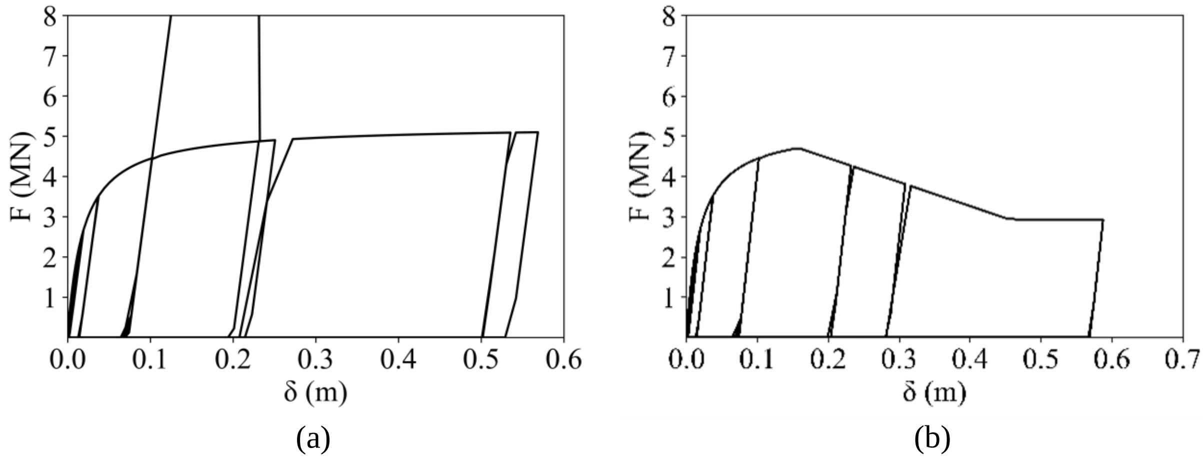


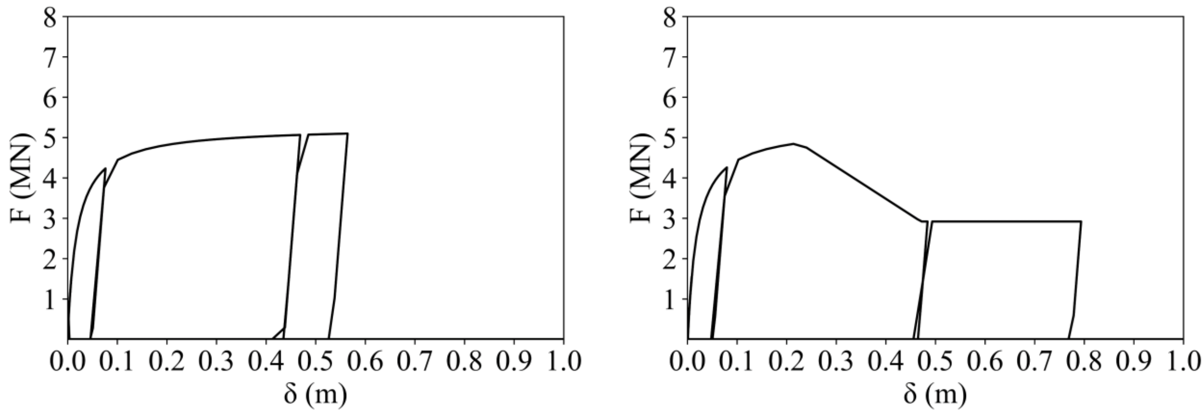
Figure 4. Force-displacement history diagrams of the abutment-backfill system of a bridge using (a) ‘Hyperbolic Gap Material’ and (b) ‘Hyperbolic Gap Softening’

3 APPLICATION OF THE PROPOSED MODEL

The previously described model was used in an extensive set of parametric analyses to verify its applicability, identify any possible numerical issues, and compare the behaviour of systems that include it with those that include the existing ‘Hyperbolic Gap Material’.

3.1 Verification using single-degree-of-freedom systems

First, the model was applied to various single-mass systems, which were subjected to a large number of response history analyses within a broad range of earthquake intensity levels. These SDOF systems consisted of a vertical beam-column element, which was fixed at its base and had an attached lumped mass to its top (the dynamic DOF was the horizontal displacement of the mass). A horizontal zero-length element was attached to the lumped mass. Half of the analyses were conducted using the ‘Hyperbolic Gap Softening’ constitutive law at the zero-length element; the other half used the ‘Hyperbolic Gap Material’. Various stiffness and mass values of the SDOF were tried, while in some analyses a plastic hinge was assigned at its bottom. No numerical difficulties were noted when the ‘Hyperbolic Gap Softening’ uniaxial material was used, except for the cases where an elastic-perfectly plastic law (zero hardening) was used at the plastic hinge of the SDOF. In such cases, the analyses with both ‘Hyperbolic Gap Softening’ and ‘Hyperbolic Gap Material’ failed as a singular SDOF stiffness matrix was formed subsequent to yielding of the plastic hinge. Furthermore, no overshooting appeared during the analyses with ‘Hyperbolic Gap Softening’. An example where the same SDOF and input ground motion were used and only the material law of the zero-length changed is shown in Figure 5. As can be noted in Figure 5, the two models resulted in notably different absorbed energies and maximum displacements.



(a) (b)

Figure 5. Force-displacement history diagrams of a zero-length element attached to the top of a single mass system using (a) 'Hyperbolic Gap Material' and (b) 'Hyperbolic Gap Softening'

3.2 Effect of softening backfill on the seismic response of bridges

A parametric study of the effect of using the 'Hyperbolic Gap Softening' in the seismic response of a typical 3-span overpass was carried out, in comparison with the response obtained using the 'Hyperbolic Gap Material' in the same model. The 99 m long reference bridge, which is a modification of an existing overpass of Egnatia Motorway in N. Greece, consists of a 45 m central and two 27 m outer spans. The 10 m wide box girder deck is monolithically connected to the two cylindrical piers, which have a diameter of 1.20 m and clear heights of 5.9 m and 7.9 m. The seat-type abutments are 5.6 m and 5.7 m high; they include 2.45 m high backwalls and each of them supports the deck through a pair of elastomeric bearings with dimensions (mm) 350 × 450 × 181 and total rubber thickness t_r = 77 mm. The bridge rests on relatively firm cohesive soil that roughly corresponds to soil class C of Eurocode 8 [30] and thus, 6 m × 6 m × 1.50 m surface footings were found to be adequate for supporting the piers. All the structural and geotechnical components of the model bridge were designed and checked according to the pertinent Eurocodes, while soil-pier foundation-structure interaction was taken into account, following the relationships given in [31]. The layout of the bridge model is shown in Figure 6.

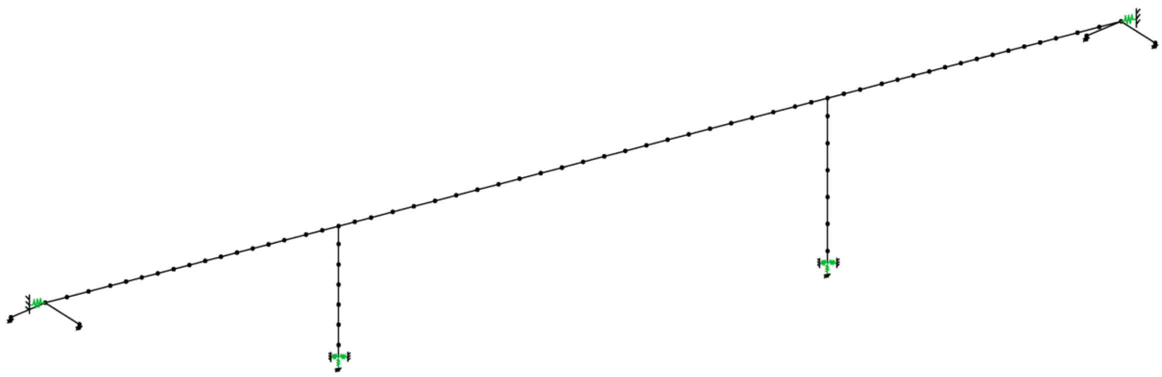


Figure 6. Structural model of the case study bridge

The case study bridge was subjected to a set of 7 spectrum-compatible artificial accelerograms parallel to its longitudinal direction, taken from a companion paper [11], scaled to various amplitudes of the design spectrum. The lowest level of seismic intensity considered was at $PGA_{,rock}$ = 0.32 g and the highest was at $PGA_{,rock}$ = 0.96 g (six times the design earthquake E_d), as backfill softening was found to occur for high intensities only. Various initial deck-abutment joint gap sizes were used in the parametric analyses (0 to 300 mm). The nonlinear behaviour of the sacrificial abutment-backfill system was modelled using a single zero-length element, with properties corresponding to an engineered granular backfill. The backbone curve of the backfill soil until the point of maximum passive resistance was calculated according to [8] and x_{max} was assumed to be equal to 3% of the backwall height, following an empirical recommendation for granular backfill soil found in [26]. The values of all the input parameters of the two hyperbolic gap models except the varying x_{gap} are listed in Table 2. The backbone curves that were used in each backfill model are presented in Figure 7.

The average of the maximum absolute values of the displacements of the abutment-backfill springs subsequent to gap closure and the pier drifts derived from the nonlinear response history analyses for various intensity levels and initial gap sizes using the two hyperbolic constitutive models are shown in Tables 3 and 4. For relatively low seismic intensities, the two models yield the same results, as expected. Notable differences are observed at the highest examined intensity levels, where the maximum difference in the maximum pier drifts and abutment displacements was about 8%. This can be attributed to the reduced lateral force that the abutment carries after the point of peak resistance in the case of the 'Hyperbolic Gap Softening' model, as shown in Figure 8b. On the contrary, in the case of the 'Hyperbolic Gap Material', the passive force remains at the level of the maximum passive resistance throughout the analysis (Figure 8a) and hence, the abutment-backfill systems relieve the piers substantially even at very large displacements. As anticipated, the differences between the two models tend to be less important as the initial joint gap becomes larger.

K_{max} (kN/m)	K_{ur} (kN/m)	x_{max} (m)	F_{ult} (kN)	x_{res} (m)	F_{res} (kN)
375,570	206,564	0.073	5,415	0.219	3,249

Table 2: Values of the input parameters of the two hyperbolic gap models used in the case study

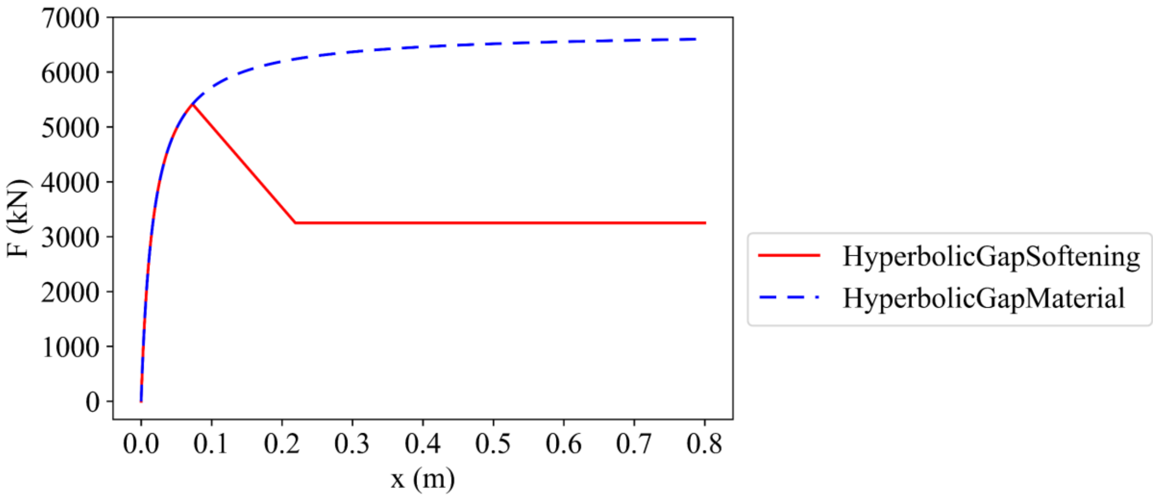


Figure 7. Backbone curves of the 'Hyperbolic Gap Softening' and 'Hyperbolic Gap Material' models used in the response history analyses with x_{gap} = 0

Gap size	Earthquake intensity (PGA,rock)					
	0.32 g		***0.96 g***		***1.28 g***	
	HG	***HGsoft***	***HG***	***HGsoft***	***HG***	***HGsoft***
0	0.059	0.059	0.320	0.345	0.474	0.505
25	0.036	0.036	0.298	0.321	0.450	0.484
50	0.019	0.019	0.270	0.292	0.428	0.462
75	-	-	0.252	0.270	0.410	0.439
100	-	-	0.232	0.248	0.389	0.413
150	-	-	0.191	0.202	0.495	0.367
300	-	-	0.074	0.074	0.215	0.228

Table 3: Comparison of the average value of the maximum abutment-backfill displacement (in m) after gap closure for the 7 input motions using the two hyperbolic gap models (Hyperbolic Gap and Hyperbolic Gap Softening).

Gap size	Earthquake intensity (PGA,rock)					
	0.32 g		***0.96 g***		***1.28 g***	
	HG	***HGsoft***	***HG***	***HGsoft***	***HG***	***HGsoft***
0	1.08%	1.07%	5.30%	5.61%	7.80%	8.30%
25	1.12%	1.12%	5.31%	5.60%	7.82%	8.36%
50	1.17%	1.17%	5.27%	5.56%	7.87%	8.40%
75	1.31%	1.31%	5.35%	5.60%	7.98%	8.43%
100	1.36%	1.36%	5.42%	5.65%	8.00%	8.42%
150	1.36%	1.36%	5.60%	5.74%	8.13%	8.50%
300	1.36%	1.36%	6.09%	6.10%	8.48%	8.70%

Table 4: Comparison of the average value of the maximum pier drift after gap closure for the 7 input motions using the two hyperbolic gap models (Hyperbolic Gap and Hyperbolic Gap Softening)

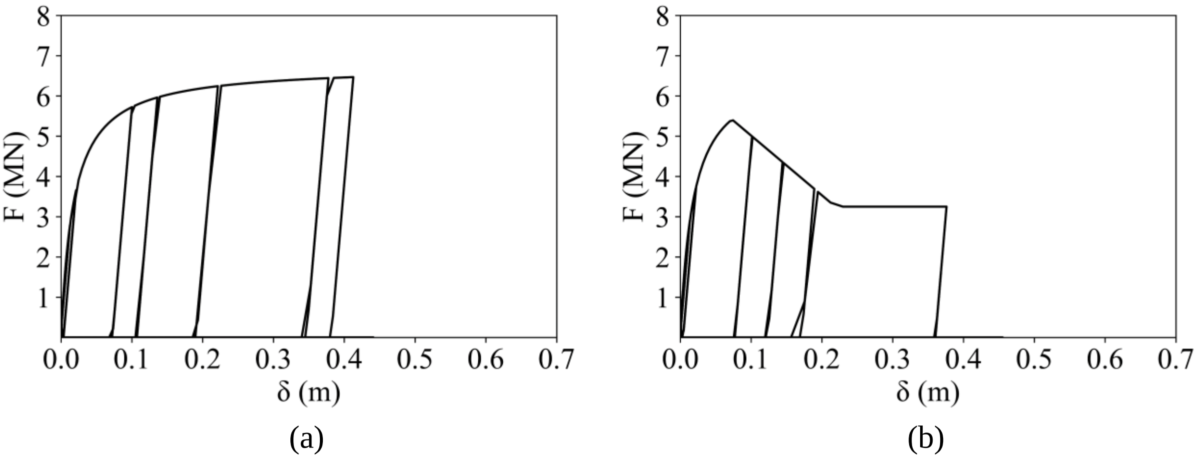


Figure 8. Force-displacement history diagrams of the abutment-backfill system (sacrificial backwall modelling) of the case study bridge subjected to a ground motion scaled to PGA = 1.28 g using (a) ‘Hyperbolic Gap Material’ and (b) ‘Hyperbolic Gap Softening’

4 CONCLUSIONS

The present study highlighted the inadequacies of the ‘Hyperbolic Gap Material’ of OpenSees if it is used in nonlinear response history analyses when significant backfill displacement develop. The ensuing softening in the response of the abutment-backfill system may be relevant, especially when a proper fragility analysis has to be carried out. The new ‘Hyperbolic Gap Softening’ OpenSees material model that is proposed herein resolves this important issue by introducing a descending and a residual branch after the point of peak resistance, using parameter values available in the literature, while it attempts to remove any ambiguities in the definition of the constitutive model of the backfill soil spring by including input parameters with a direct physical meaning. The difference in the definition of the backbone curve of the backfill spring seems to lead to notable differences not only in the response of the abutment-backfill per se but also in the response of other seismically critical bridge components, such as the piers. In cases where only large joint gaps or low seismic intensities are considered, the existing ‘Hyperbolic Gap Material’ produces quite accurate results. However, the new model did not exhibit any numerical difficulties throughout the case studies wherein it was used; instead, it solved the overshooting problems that occur occasionally when the existing OpenSees material is used. Furthermore, its response under ground motions of low intensity is the same as the response of ‘Hyperbolic Gap Material’ when equivalent input parameters are used. Thus, in the authors’ opinion, it is the preferred option when OpenSees is used in fragility analysis to capture the advanced damage states, especially when these are controlled by damage in the backfill.

Except for the joint gap size and seismic intensity, the importance of the accurate representation of the post-peak backfill behaviour seems to depend on the structural configuration of the entire bridge. This conclusion is based on the observation that the significant differences that the two compared models exhibited in the analysis of a single mass system were mitigated to some extent when the models were incorporated into the model of an entire bridge. For that reason, a large number of analyses considering a variety of bridge structural characteristics has to be carried out using both models, not only to further verify the applicability of the proposed model but also to draw reliable conclusions regarding the effect that the modelling of the full-range response of the abutment-backfill system has on the seismic response of bridges.

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