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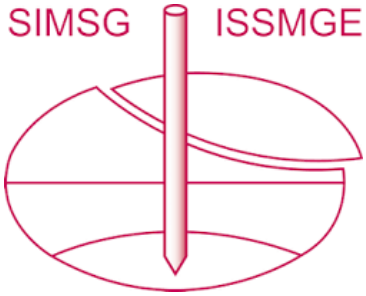

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A combined rate and ratcheting model for modelling monopile behaviour

Un modèle capturant les effets de vitesse et de cliquet pour des monopieux

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ABSTRACT: This paper presents a combined rate and ratcheting model to capture the increased lateral foundation capacity of a monopile under rapid loading, and the accumulated pile displacement under cyclic loading. The model builds on the Masing-Iwan model by adding a ratcheting element and non-linear damper elements. This is integrated in the PISA 1D model, which is a generalised Winkler model for monopile foundations with four soil-reaction components: the distributed lateral soil reaction, the distributed moment reaction, the base horizontal force and the base moment. In the PISA project, pile testing has been performed at two sites: Cowden with an over-consolidated glacial till profile and Dunkirk with a dense marine sand profile. The parameters for the rate and ratcheting model are calibrated to field tests at both sites and the results are presented. The combined rate and ratcheting model allows integration of rate effects into modelling the cyclic behaviour. This may be of interest when a high peak load is considered in design for offshore wind turbines, which may only occur for a short period, for instance due to a freak wave.

RÉSUMÉ : Cet article présente un modèle combiné de vitesse et de cliquet pour capturer la capacité de fondation latérale accrue sous chargement rapide et le déplacement de pieu accumulé sous chargement cyclique. Le modèle s'appuie sur le modèle Masing-Iwan en ajoutant un élément à cliquet et des éléments amortisseurs non linéaires. Ceci est intégré dans le modèle PISA 1D, qui est un modèle Winkler généralisé pour les monopieux avec quatre composants de réaction du sol: la réaction latérale distribuée du sol, la réaction du moment distribué, la force horizontale de base et le moment de base. Dans le cadre du projet PISA, des tests de pieux ont été réalisés sur deux sites: Cowden avec un profil de till glaciaire sur-consolidé et Dunkerque avec un profil de sable marin dense. Les paramètres du modèle de vitesse et de cliquet sont calibrés pour des essais sur le terrain sur les deux sites et les résultats sont présentés. Le modèle combiné de vitesse et de cliquet permet d'intégrer les effets de vitesse dans la modélisation du comportement cyclique. Cela peut être intéressant lorsqu'une charge de pointe élevée est prise en compte dans la conception des éoliennes offshore, ce qui ne peut se produire que pendant une courte période, comme une vague anormale. (« Monopieu, charge rapide, cyclique »).

KEYWORDS: monopile, rate and ratcheting model.

1 INTRODUCTION

Offshore wind turbines are subject to harsh environmental conditions. The foundations need to be adequately designed to sustain the cyclic and dynamic loads from the interaction of the structure with the aerodynamic and hydrodynamic loads.

The PISA project provided new design guidance for monopile foundations, which are the preferred foundation method for the majority of offshore wind turbines. The design method focuses on the foundation response under monotonic loading, accurately capturing the foundation deformation from the initial stiffness up to ultimate failure conditions. To validate the PISA design method, field tests were performed at two sites which were deemed representative for soil profiles found in offshore wind projects: Cowden UK with a glacial clay till profile and Dunkirk France with a dense marine sand profile (Byrne *et al.* 2020c, McAdam *et al.* 2020).

The testing program of the PISA project also offered scope to test the foundations under rapid and cyclic loading sequences (Byrne *et al*. 2020b). At Cowden, pile CM6 was tested under a combined monotonic and cyclic loading routine. CM5, was tested under a large number of cycles and CM1 was tested at different rates of loading. At Dunkirk, pile DM6 was tested at different rates of loading combined with a limited number of cycles and DM2 was tested under a large number of cycles. This offered important insights for the rate and ratcheting response of monopiles in clay and sand. The rate and ratcheting response are analysed and modeled individually in Beuckelaers *et al*. 2020 and Beuckelaers *et al*. 2021.

This paper focuses on the tests where both rate and ratcheting effects can be observed clearly: CM6 and DM6. A model is developed which captures both effects and can be used as an extension of the PISA 1D model. The model is calibrated to the results of both tests showing reasonable agreement. Use of the rate and ratcheting model in combination with the PISA design methodology results in a pragmatic method for modelling foundations under rapid and cyclic loading.

2 RATE AND RATCHETING IN GENERALISED WINKLER MODEL

The generalised Winkler approach is illustrated in Figure 1 with the soil reactions from the PISA 1D model: lateral distributed reaction p, distributed moment m, base horizontal force H_B and base moment M_B. The lateral load H is applied at a vertical eccentricity h, and L is the embedded length of the foundation. In the PISA 1D model, the soil reaction components are defined as functions of the normalised pile displacement or rotation (see Byrne *et al*., 2020a and Burd *et al*., 2020). In this paper, the soil reaction curves are extended to the parallel rate and ratcheting model, illustrated in Figure 2, for which the parameters are defined below. The parallel version of the model is used in this paper, although the series version can represent the same behaviour in 1D loading using appropriate calibration of the parameters. The model can be calibrated to approximate the soil reaction curves for monotonic loading and to capture the rate and ratcheting response under rapid and cyclic loading. The parallel rate and ratcheting model is presented in stress-strain $(\sigma - \epsilon)$

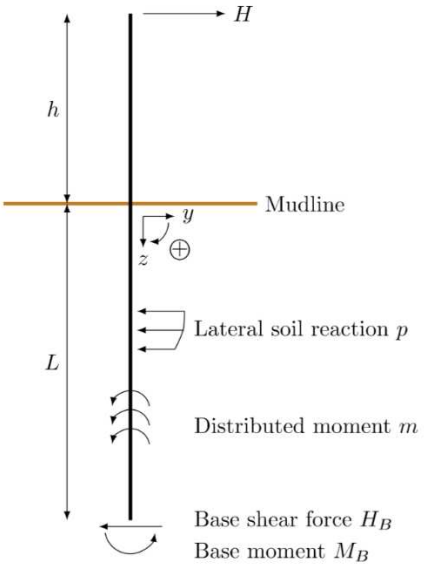

Figure 1. Key features of the 1D PISA model (after Byrne *et al*., 2020).

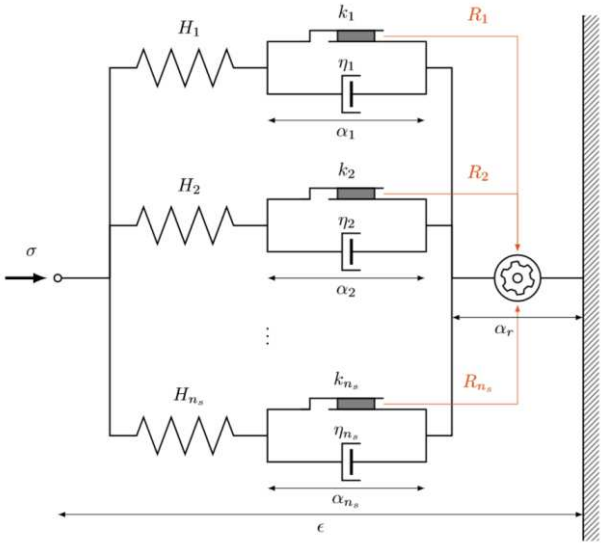

Figure 2. The combined rate and ratcheting model.

space, however, for application in the 1D model, these variables may represent each of the soil reaction curves: the distributed load-displacement $(p-v)$, the distributed moment-rotation $(m-\psi)$, the base horizontal force-displacement (H_B-v_B), or the base moment-rotation $(M_B-\psi_B)$.

Model behaviour in the hyperplasticity framework (Houlsby and Puzrin, 2006) can be derived entirely from two potential functions. The HARM framework, Houlsby *et al*. (2017) is used to model ratcheting. The energy potential f and force potential z for the model in Figure 2 are:

$$f = \sum_{i=1}^{n_s} \frac{H_i}{2}(\epsilon - \alpha_i - \alpha_r)^2 \quad (1)$$

$$z = \sum_{i=1}^{n_s} k_i \left[|\dot{\alpha}_i| + \eta \left(\dot{\alpha}_i + \sinh^{-1}\left(\frac{\dot{\alpha}_i}{\dot{\alpha}_{\mathrm{qs}}}\right) - \sqrt{\dot{\alpha}_i^2 + \dot{\alpha}_{\mathrm{qs}}^2} + \dot{\alpha}_{\mathrm{qs}} \right) \right] + \sigma \dot{\alpha}_r \quad (2)$$

where H_i are the hardening moduli of the springs, k_i are the strengths of the slider elements, α_i are the hardening strain variables of the sliders and α_r is the ratcheting strain. The index i ranges from 1 to n_s, the number of spring-slider-damper elements in the model. The parameter η is the viscous constant and $\dot{\alpha}_{\mathrm{qs}}$ is the quasi-static strain rate: both of which are set constant for each of the elements. For $\dot{\alpha}_i \gg \dot{\alpha}_{\mathrm{qs}}$, the strength increase due to the dashpot is related to:

$$\frac{\chi}{k} - 1 \sim \eta \log\left(2\frac{\dot{\alpha}_i}{\dot{\alpha}_{\mathrm{qs}}}\right). \quad (3)$$

For every tenfold increase in strain rate, the apparent strength is therefore approximately increased by: $\eta_{10} = \eta \log 10$. From the energy function, the stress in the model can be derived.

$$\sigma = \partial f / \partial \epsilon = \sum_{i=1}^{n_s} H_i(\epsilon - \alpha_i - \alpha_r) \quad (4)$$

The constraint equation for the ratcheting strain defines the accumulation process:

$$\dot{\alpha}_r = \mathrm{S}(\sigma) \sum_{i=1}^{n_s} R_i |\dot{\alpha}_i| \quad (5)$$

where R_i are the coupling terms between the sliders and the ratcheting element. $\mathrm{S}(\sigma)$ is the generalised signum function of the stress, such that the accumulation of ratcheting strain is always in the same direction of the stress. It is observed that the ratcheting depends on the load history and therefore an additional constraint equation can be written to capture the load history effect on the ratcheting strain. Many possibilities exist for the definition of this hardening parameter (see Houlsby *et al*., 2017). In line with Beuckelaers *et al*. 2020, the selected formulation in this paper is:

$$\dot{\alpha}_h = |\dot{\alpha}_r| \quad (6)$$

A fast method to capture the incremental response of this model is defined in Beuckelaers (2017).

3 CALIBRATION OF THE BACKBONE CURVE

The calibration of the backbone curves for the soil reaction in the PISA 1D methodology follows two steps:

1. Soil reaction curves are calibrated to the reactions of a 3D FE foundation model using the parameterised method in the PISA project (method described in: Byrne *et al*., 2020a; Burd *et al*., 2020; adopted soil reaction parameters in: Beuckelaers 2017).
2. The stiffness and strength parameters of the reaction curves are adjusted by correction factors to fit the reaction to the field tests at the end of the load holding periods.

This method is illustrated in Figure 3 for test CM6 and DM6. Both piles have a 762mm diameter, 4m embedment and 10m loading eccentricity. The wall thickness is 11mm and 19mm for CM6 and DM6 respectively. The initial backbone curve gives a reasonable prediction for the reaction of the pile behaviour of DM6. The correction factors in step 2 are applied to all reaction curves to provide an improved match to the measured quasi-static backbone curve, which can be used as a basis for the cyclic modelling. Two correction factors are used: A_0 on the stiffness and A_u on the ultimate reaction of the soil reaction curves. The values are obtained from an optimisation process to fit the calibration points and are given in Table 1. The calibration points are specified at the end of the hold phases or slightly below the backbone curve when fast loading is applied. We note that the initial soil reaction curves were established for much larger piles and therefore the values in Table 1 deviate from unity.

Table 1. Calibration parameters for the monotonic backbone curves.

Parameter	CM6	DM6
A_0 (initial stiffness)	0.2777	0.5652
A_u (ultimate resistance)	0.6268	1.2178

4 CALIBRATION OF THE RATE AND RATCHETING MODEL

The calibration of the rate and ratcheting model uses a single set of parameters, which is applied to all four components of the soil reaction. To capture the effects of load magnitude and load history in this calibration study, the ratcheting coupling terms are defined as:

$$R_i = R_0 \left(\frac{|\sigma|}{\sigma_u}\right)^{m_s} \left(\frac{\alpha_h}{\alpha_{h0}}\right)^{m_h} k_i \sigma_u \tag{7}$$

where R_0 is a constant, α_{h0} is the initial hardening parameter. σ_u is the ultimate resistance of the model $\left(\sigma_u = \sum_{i=1}^{n_s} k_i\right)$, m_s is the stress power coefficient and m_h is the hardening power coefficient. Combining equation 7 with the constraint equation of the ratcheting strain gives:

$$\dot{\alpha}_r = \mathrm{S}(\sigma) \sum_{i=1}^{n_s} R_0 \left(\frac{|\sigma|}{\sigma_u}\right)^{m_s} \left(\frac{\alpha_h}{\alpha_{h0}}\right)^{m_h} \frac{k_i}{\sigma_u} |\dot{\alpha}_i| \tag{8}$$

The power coefficients m_s and m_h can be derived analytically to capture the effect of load magnitude and cyclic load history (Abadie *et al*. 2019). The initial hardening parameter is set to a small fraction of the ultimate strain of the soil-reaction curves $(\alpha_{h0} = \epsilon_u/100)$. The constant R_0 is calibrated manually in this paper; we note that the combined effect of rate and ratcheting complicates any analytical derivation of this constant. The ratcheting element results in a shift of the backbone curve upon initial loading, which is taken into account when the strength k_i and stiffness H_i parameters are calculated (see Beuckelaers *et al*. 2020).

For the rate parameters, $\dot{\alpha}_{\mathrm{qs}}$, the quasi-static strain rate is set to:

$$\dot{\alpha}^{v}_{\mathrm{qs}} = \frac{0.1\,\mathrm{D}}{6\mathrm{h}}; \qquad \dot{\alpha}^{\psi}_{\mathrm{qs}} = \frac{2^\circ}{6\mathrm{h}} \tag{9}$$

which are the average rates of ground level displacement and rotation during the monotonic tests, performed over a time of approximately 6h. The viscous constant η_{10}, which defines the logarithmic strength increase with rate, is calibrated based on the fast loading tests CM1 and DM6 and the monotonic load tests in Beuckelaers *et al.* 2021. The combined set of parameters for the rate and ratcheting model for CM6 and DM6 are given in Table 2. Note that although the R_0 factors seem large, when combined with the terms in Equation 7, the resulting ratcheting strain is only a small fraction of the plastic strain.

Table 2. Calibration parameters for the rate and ratcheting model.

Parameter	CM6	DM6
R_0 (ratcheting constant)	10 000	2 000 000
m_s (stress power coefficient)	9.0	9.0
m_s (hardening power coefficient)	-2.2	-2.2
η_{10} (viscous constant)	0.12	0.6

5 RESULTS

The modelling approach is applied to CM6 and DM6 where both the rate and ratcheting effects can be observed clearly.

5.1 *Cowden (CM6)*

For test CM6 in Cowden, the monotonic loading routine is combined with cyclic loading. The load steps are performed to have a constant displacement rate of $\dot{v}_G = D/300\mathrm{min}$ and the load holds were sustained until the creep displacement rate slowed down to $\dot{v}_G < D/100000\mathrm{min}$. The creep during the load holds of the field tests indicate that higher lateral pile capacity can be reached when the pile is loaded at a higher rate. Cyclic loading was applied at three different load levels: 9 cycles at 42.5kN, 9 cycles at 70kN and 37 cycles at 90kN. The ground level response in Figure 3 clearly indicates the importance of the load magnitude on the ratcheting effect.

Both the rate and ratcheting behaviour of the foundation pile are captured reasonably well in the calibrated model (see figure 4). The rate characteristics of the model, and the test, are exhibited via the creep behaviour that is evident during the load holds. The capacity increase in the load steps at 70kN and 90kN is slightly underpredicted, but the overall rate response (creep during load holds and increased capacity during the load steps) is in line with the measured response. The magnitude of ratcheting at the three different load levels is also captured accurately. We note that the calibration parameters are only based on a limited number of tests and that further research may be required to use these parameters when making predictions for other foundation piles.

The distributed lateral soil reaction of the simulation is shown in Figure 5, noting that the rate and ratcheting model is applied to all four soil reaction components. In Figure 5, note that (a) at the highest elevation the displacements are of course largest, (b) further down the pile the displacements are smaller, but the reactions larger because of the higher soil stiffness and

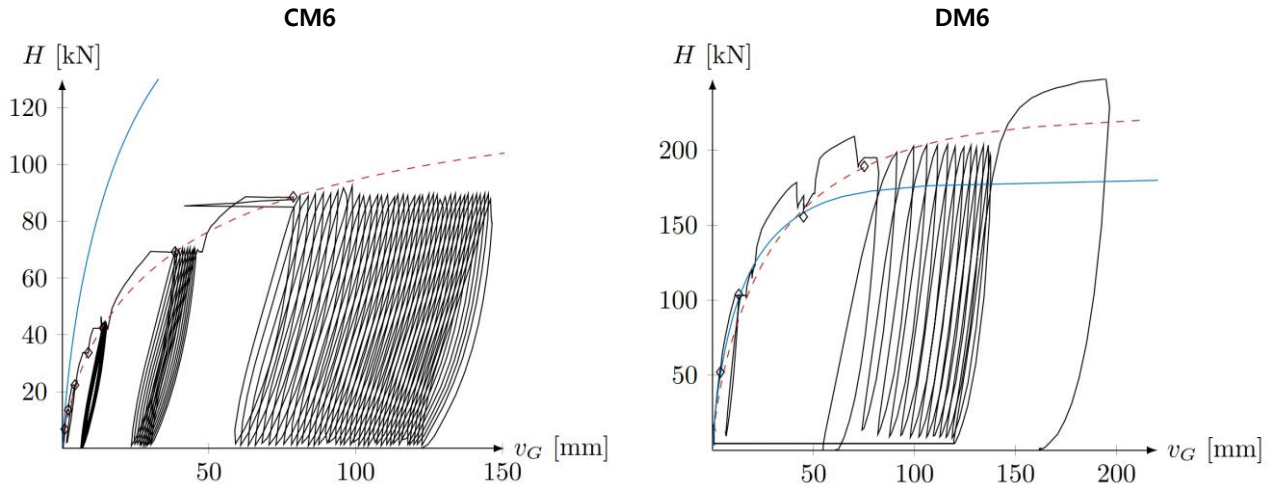

Figure 3. Field test response of CM6 and DM6 (–) compared to the simulated backbone curve using the initial (–) and the recalibrated parameterised soil reaction curves (- -) to the calibration points (◊).

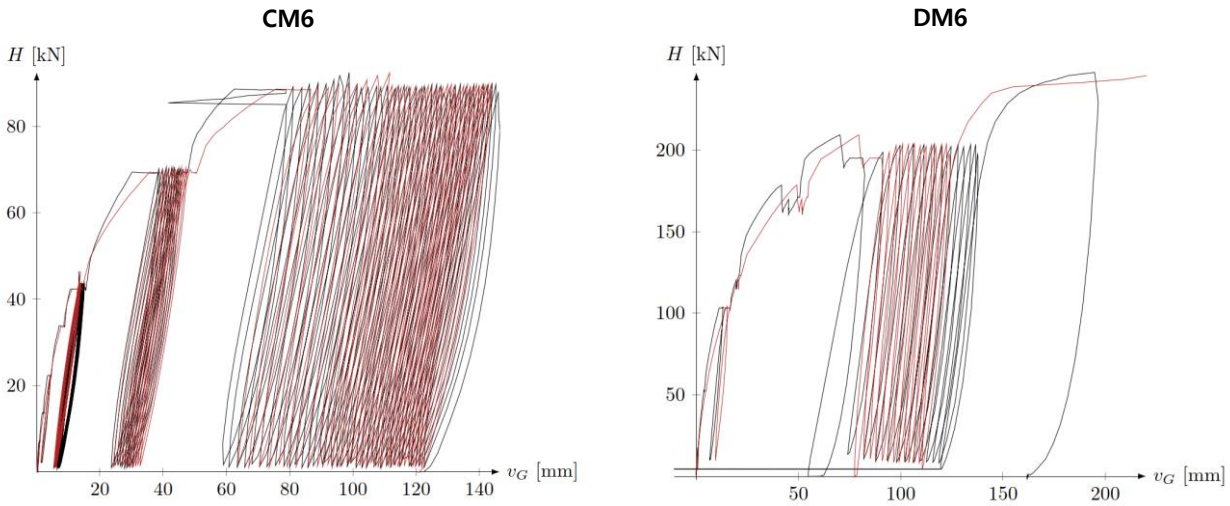

Figure 4. Simulated response of CM6 and DM6 (–) compared to the field test response (–).

strength, (c) towards the toe of the pile the displacements are in the reverse direction. This figure also shows how the soil reaction redistributes due to both rate and ratcheting effect. The rate effects are more apparent near ground level, where larger displacements are mobilised. Especially at shallow depths (see curve for z=0.5m), the soil reaction does not follow a smooth backbone curve during the load steps, which is caused by the rate effect. During cyclic loading, the larger amount of ratcheting in the shallow layers results in a redistribution of the soil reaction, where more and more resistance is carried by the lower layers as cyclic loading continues. This is evidenced by the peaks of the distributed load at z=0.5m, which reduce with cycle number.

5.1 *Dunkirk (DM6)*

For DM6 in Dunkirk, the fast loading routine was combined with cyclic loading. The fast loading routine explicitly measures the rate effect by applying load steps at different rates. This is contrast with CM6, where the rate effect is partially exhibited through the creep in the load holds. The fast load steps were performed at displacement rates of 330mm/min and the slower load steps at 0.45mm/min to 2.5mm/min. Cyclic loading was subsequently performed with 12 cycles at 200kN and finally a monotonic push was performed.

Figure 4 shows the measured and simulated ground level response of the pile. The capacity increase due to the rate effects appear to be captured adequately, though the simulated response is slightly shifted, which may be caused by the selection of the backbone curve. Subsequent cyclic loading results in ratcheting which is also captured in the model. In the final push, the model resulted in very large displacements, though we note that the calculated displacements at ultimate capacity are very sensitive to the selection of the backbone curve and that this result could be corrected using a slightly different backbone curve for the basis of the rate and ratcheting model.

6 CONCLUSIONS

A combined rate and ratcheting model is presented which is incorporated in the PISA 1D model, implemented as a multi-surface plasticity model. This modelling approach provides a rigorous method to capture monopile foundation response under rapid and cyclic loading, consistent with the PISA design framework. Two piles of the PISA project were simulated: CM5 in an over-consolidated clay till profile and DM5 in a dense marine sand profile. The results show that with appropriate calibration of the model parameters, the simulated response adequately captures the observed foundation behaviour. Further work may be required on the calibration of the model parameters based on soil element testing, so that predictions for the foundation response can be performed at design stage of an offshore wind project. The rate and ratcheting model allows for assessing the foundation capacity increase under fast loading as well as the accumulated rotation of the foundation under cyclic loading. The interaction of both effects may be important when large cyclic loading is applied over short durations which may occur during storm loading events.

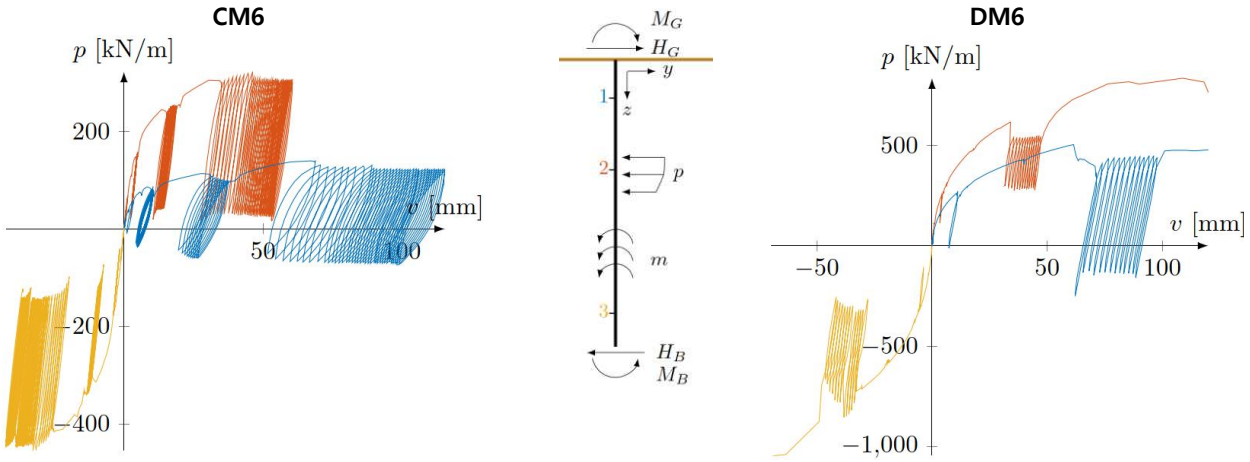

Figure 5. Simulated lateral soil reaction response for CM6 and DM6 using the combined rate and ratcheting model at 1: z=0.5m, 2: z=1.5m and 3: z=3.5m.

7 ACKNOWLEDGEMENTS

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