UDC 699.841
IRSTI 67.11.03
RESEARCH ARTICLE

THE COMPARISON OF DEFORMATION CALCULATION RESULTS OF STRUCTURES UNDER SEISMIC IMPACT USING MOHR-COULOMB AND HARDENING SOIL SMALL (HSS) SOIL MODELS

A.S.Shadkam[1,*], **E.T.Bessimbayev**[1], **U.T.Begaliev** [2], **S.E. Niyetbay**[1]

[1]Satbayev University, 050013, Almaty, Kazakhstan
[2]International University of Information Technology Corporation, 720044, Bishkek, Kyrgyzstan

Abstract. *This study examines the behavior of buildings under seismic impacts considering different soil models. Nowadays, along with the use of numerical methods in the analysis and design of engineering projects, it is known that this method is widely used in the analysis of problems related to geotechnical engineering construction. Comparative data on displacements, moments, and forces have been obtained for the Mohr-Coulomb soil model and the Hardening Soil Small (HSS) model. The software Plaxis 2D is used for the analysis of both models. The application of such complexes requires special attention to soil foundation models and parameter assignment. The selection of appropriate parameters and soil models can significantly influence the results of numerical analysis. The Mohr Coulomb elastic-plastic model is one of the most widely used models adopted in cases of hardness estimation of materials independent of surface tension. However, it was found that, the stress stiffness in the behaviour model and the difference in stiffness between initial loading and unloading/re-loading are important modelling aspects when discussing seismic effects and play an important role in predicting ground motions. A comprehensive comparison of the results for the Mohr-Coulomb and Hardening Soil models reveals several important differences, which are presented in this article.*

Keywords: *Plaxis 2D, Hardening Soil Small, Mora-Coulomb, hardening, soil model.*

***Corresponding author**
Shadkam Assylbek, e-mail: asylbek-96@list.ru

https://doi.org/10.51488/1680-080X/2024.4-16
Received 01 September 2024; Revised 03 October 2024; Accepted 15 November 2024

ӘОЖ 699.841
FTAMP 67.11.03
ҒЫЛЫМИ МАҚАЛА

МОР-КУЛОН ТОПЫРАҒЫ МЕН HARDENING SOIL SMALL (HSS) МОДЕЛЬДЕРІ БОЙЫНША СЕЙСМИКАЛЫҚ ӘСЕРЛЕРГЕ КОНСТРУКЦИЯЛАРДЫҢ ДЕФОРМАЦИЯЛАРЫН ЕСЕПТЕУ НӘТИЖЕЛЕРІН САЛЫСТЫРУ

А.С.Шадкам[1,*], Е.Т.Бесимбаев[1], У.Т.Бегалиев [2], С.Е. Ниетбай[1]

[1]Сәтпаев университеті, 050013, Алматы, Казахстан
[2]Халықаралық ақпараттық технологиялар университеті, 720044, Бішекек, Қырғызстан

Аңдатпа. *Бұл зерттеу әртүрлі топырақ үлгісіндегі сейсмикалық әсерлердегі ғимараттардың мінез-құлқын қарастырады. Қазіргі уақытта инженерлік жобаларды талдау және жобалау кезінде сандық әдістерді қолданумен қатар, бұл әдіс инженерлік-геологиялық құрылысқа қатысты тапсырмаларды талдауда кеңінен қолданылатыны белгілі. Мора-Кулон топырақ моделі үшін қозғалыстар, моменттер, күш-жігер және топырақты қатайтатын Hardening soil small моделі бойынша салыстырмалы деректер алынды. Осы модельдердің екеуін де талдау үшін plaxis 2D бағдарламалық жасақтамасы қолданылады. Мұндай кешендерді қолдану топырақ негізінің модельдеріне және параметрлердің мақсатына ерекше назар аударуды қажет етеді. Тиісті параметрлер мен топырақ моделін таңдау сандық талдау нәтижелеріне айтарлықтай әсер етуі мүмкін. Кулонның серпімді-пластикалық Мора моделі-беттік керілуге қарамастан материалдардың қаттылығын бағалау жағдайында қабылданған ең көп қолданылатын модельдердің бірі. Дегенмен, мінез-құлық үлгісіндегі кернеу қаттылығы және бастапқы жүктеме мен түсіру/қайта жүктеу арасындағы қаттылық айырмашылығы сейсмикалық әсерлерді талқылау кезінде модельдеудің маңызды аспектілері болып табылатыны және топырақтың ауытқуын болжауда маңызды рөл атқаратыны анықталды. Мора-Кулон жағдайлары мен топырақтың қатаюы үшін нәтижелерді толық салыстыру осы мақалада келтірілген кейбір маңызды айырмашылықтарды береді.*

Түйін сөздер: *Plaxis 2D, Hardening Soil Small, Мора-Кулон, қатайту, топырақ моделі*.

***Автор-корреспондент**
Шадқам Асылбек, e-mail: asylbek-96@list.ru

https://doi.org/10.51488/1680-080X/2024.4-16
Алынды 01 қыркүйек 2024; Қайта қаралды 03 қазан 2024; Қабылданды 15 қараша 2024

УДК 699.841
МРНТИ 67.11.03
НАУЧНАЯ СТАТЬЯ

СРАВНЕНИЯ РЕЗУЛЬТАТОВ РАСЧЕТА ДЕФОРМАЦИЙ КОНСТРУКЦИЙ НА СЕЙСМИЧЕСКОЕ ВОЗДЕЙСТВИЯ ПО МОДЕЛЯМ ГРУНТА МОРА-КУЛОНА И HARDENING SOIL SMALL (HSS)

А.С.Шадкам[1,*], Е.Т.Бесимбаев[1], У.Т.Бегалиев[2], С.Е. Ниетбай[1]

[1]Сатпаев университет, 050013, Алматы, Казахстан
[2]Международный университет информационных технологий, 720044, Бишкек, Кыргызстан

Аннотация. *В этом исследования рассматривается поведение зданий при сейсмических воздействиях при разной модели грунта. В настоящее время, наряду с использованием численных методов при анализе и проектировании инженерных проектов, известно, что этот метод широко применяется при анализе задач, связанных с инженерно-геологическим строительством. Получены сравнительные данные по перемещениям, моментам, усилиям для модели грунта Мора-Кулона и модель твердеющий грунта Hardening soil small. Для анализа обеих этих моделей используется программное обеспечение Plaxis 2D. Применение таких комплексов требует особого внимания к моделям грунтового основания и назначения параметров. Выбор соответствующих параметров и модели грунта может оказать существенное влияние на результаты численного анализа. Упруго-пластическая модель Мора Кулона - одна из наиболее широко используемых моделей, принимаемых в случаях оценки твердости материалов независимо от поверхностного натяжения. Однако было обнаружено что, жесткость по напряжению в модели поведения и разница в жесткости между начальной нагрузкой и разгрузкой/повторной нагрузкой являются важными аспектами моделирования при обсуждении сейсмических воздействий и играют важную роль в прогнозировании колебаний грунта. Полное сравнение результатов для случаев Мора-Кулона и упрочнения почвы дает некоторые важные различия, которые представлены в этой статье.*

Ключевые слова: *Plaxis 2D, Hardenig Soil Small, Мора-Кулона, упрочнения, модель грунта.*

***Автор-корреспондент**
Шадкам Асылбек, e-mail: asylbek-96@list.ru

https://doi.org/10.51488/1680-080X/2024.4-16
Поступило 01 сентября 2024; Пересмотрено 03 октября 2024; Принято 15 ноября 2024

ACKNOWLEDGEMENTS/SOURCE OF FUNDING

This research is funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. BR21882292 – "Integrated development of sustainable construction industries: innovative technologies, optimization of production, effective use of resources and creation of technological park").

CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Жұмыс Қазақстан Республикасы Ғылым және жоғары білім министрлігінің Ғылым комитетінің қолдауымен "Тұрақты құрылыс саласын интеграцияланған дамыту: инновациялық технологиялар, өндірісті оңтайландыру, ресурстарды тиімді пайдалану және технологиялық парк құру" BR21882292 бағдарламалық нысаналы қаржыландыру шеңберінде орындалды.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ екенін растайды.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Работа выполнена в рамках программно-целевого финансирования BR21882292-«Интегрированное развитие устойчивой строительной отрасли: инновационные технологии, оптимизация производства, эффективное использование ресурсов и создание технологического парка» при поддержке Комитета науки Министерства науки и высшего образования Республики Казахстан.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы подтверждают, что конфликта интересов нет.

1 INTRODUCTION

One of the most successful examples is the ideal elastoplastic Mohr-Coulomb model. Based on typical results from indoor soil tests, this model describes the stress-strain conditions across the entire range of load variations up to the limit values. However, many years have passed since the development of this model, and today there are models that surpass it in terms of the realistic representation of soil behavior (**Sokolova, 2021**).

The Hardening Soil (HS) and Hardening Soil Small (HSS) models have recently gained popularity among designers. This is primarily due to the active urban development, which demands precise and cost-effective calculations for excavations and assessments of impacts on neighboring buildings, for which the HSS model is essential (**Schanz et al., 1999, Benz et al., 2009**).

2 LITERATURE REVIEW

A nonlinearly deformable spherical elastoplastic model, reinforced with volumetric compression and shear, accounts for the natural stress state of the soil. It distinguishes between primary and secondary loads. This model is recommended for drilling and similar tasks where shear deformation dominates. It can be used for modeling weak soils (but only if the model's behavior and laboratory curves can be verified), viscous soils, and sandy soils. It optimally describes loading and unloading tasks (**Alekseev et al., 2019**). This model represents an evolution of the hardening soil model, which accounts for low-stress areas. Unlike the hardening soil model, it better captures the consequences of deformation and more accurately determines compressible layers and zones that affect nearby buildings. Recently, the HSS (hardening soil) model or the hardened soil model has been widely used in soil environment calculations. These models are typically divided into specific groups characterized by independent laws of soil behavior under different deformation modes. The Hardening Soil model corresponds more closely to the actual behavior of soil as it uses a hyperbolic relationship between strain and deviatoric stress. The main advantage of using the hardening soil model is that it allows for the consideration of plastic deformation under different loading paths. However, it also has some drawbacks. Firstly, the complexity of applying the model to real-world practical tasks, and secondly, the excessive strain on the model due to mathematical dependencies (**Vakili et al., 2013**).

3 MATERIALS AND METHODS

In this article, we describe a comparison between parameter selection and calculation results for a soil model, conducted using the Plaxis 2D software package. The task was set in a two-dimensional configuration. Engineering-geological data were taken from specific sections typical of Almaty. In this study, a soil mass of 10×10 meters was modeled, and characteristics were sequentially assigned to each engineering-geological element (EGE) selected from a typical geological profile of Almaty. Special attention was given to silty and clayey soils with low strength and stiffness properties **(Figure 1)**.

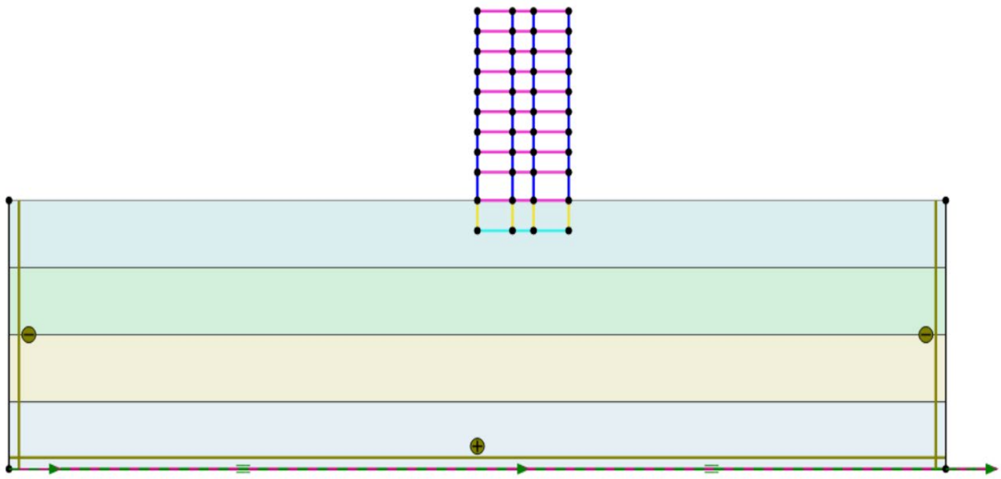


Figure 1 – Calculation scheme (author's material).

Table 1
Basic soil characteristics and additional parameters for the Mora-Coulomb and HSS models

Name of soil	Main characteristics of soils	Additional parameters for the HSS model
IGE-1. dusty grey sandy loam with plant remains, with interlayers of sand, flowing	γ=18.8 kN/m³, ν=0.35, c=7 кПа, ϕ= 21, E=5400 kPa.	E_{50}^{ref}=5400 kPa, E_{oed}^{ref}=5400 kPa, E_{ur}^{ref}=16200 kPa, Ko=0.642, G=74644 kPa, $\gamma_{0.7}$=0.34*10^{-3}
IGE-2. dusty grey grey loams, vaguely layered with plant remains, flowing	γ=18.9 kN/m³, ν=0.35, c=4 kPa, ϕ= 17, E=5000 kPa.	E_{50}^{ref}=5000 kPa, E_{oed}^{ref}=5000 kPa, E_{ur}^{ref}=15000 kPa, Ko=0.708, G=75203 kPa, $\gamma_{0.7}$=0.376*10^{-3}
IGE-3. dusty grey sandy loam with gravel, pebbles, with interlayers of loam, plastic	γ=21.4 kN/m³, ν=0.35, c=20 kPa, ϕ= 21, E=12000 kPa.	E_{50}^{ref}=12000 kPa, E_{oed}^{ref}=12000 kPa, E_{ur}^{ref}=36000 kPa, Ko=0.642, G=136620 kPa, $\gamma_{0.7}$=0.248*10^{-3}
IGE-4. dusty grey sandy loam with gravel, boulders with loam interlayers hard	γ=21.8 kN/m³, ν=0.35, c=21 kPa, ϕ= 30, E=16000 kPa.	E_{50}^{ref}=16000 кПа, E_{oed}^{ref}=16000 kPa, E_{ur}^{ref}=48000 kPa, Ko=0.5, G=149326 kPa, $\gamma_{0.7}$=0.258*10^{-3}

The building is located in the city of Almaty. It is a 12-story building with a basement. The basement height is 4.5 meters, and the typical floor height is 3 meters. The building's width is 15.6 meters, and its length is 30 meters. The structural system of the building is a wall-frame system. The thickness of the basement walls is 300 mm, while the walls above the basement are 200 mm thick. The thickness of the foundation slab is 1000 mm, made of concrete class B25. The foundation slab has a preparation layer of 100 mm, made of concrete class B7.5.

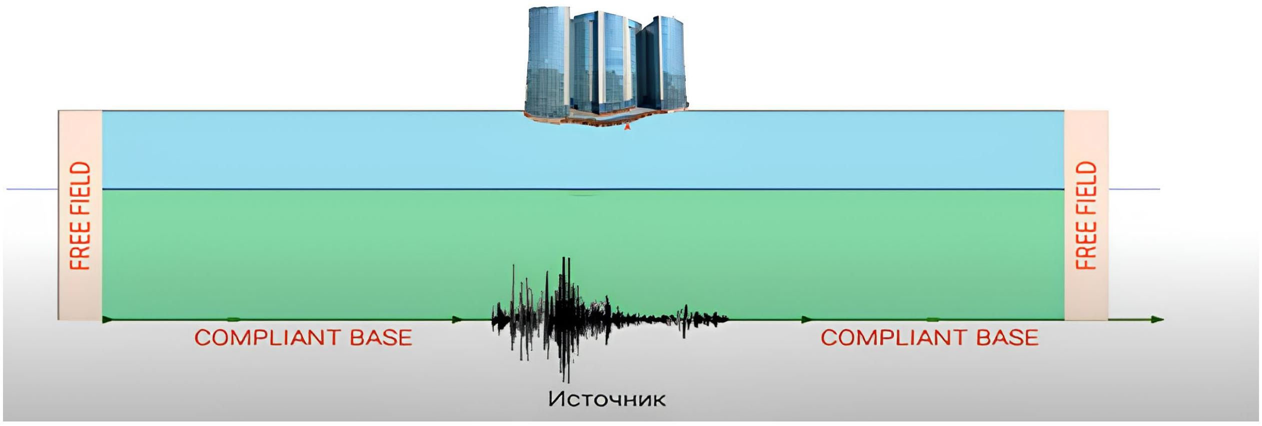
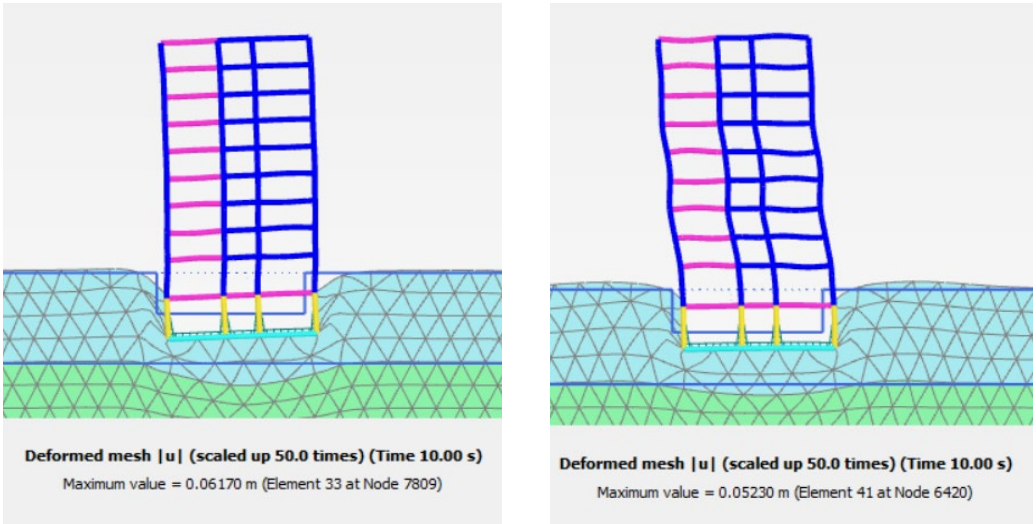


Figure 2 – Boundary conditions in PLAXIS 2D (author's material).

When performing calculations using the finite element method, it is essential to correctly assign boundary conditions. Seismic waves generated within and beyond the computational model can propagate over long distances, so the boundaries of the computational model must accurately reflect the real conditions that need to be simulated (**Brinkgreve et al., 2011**).

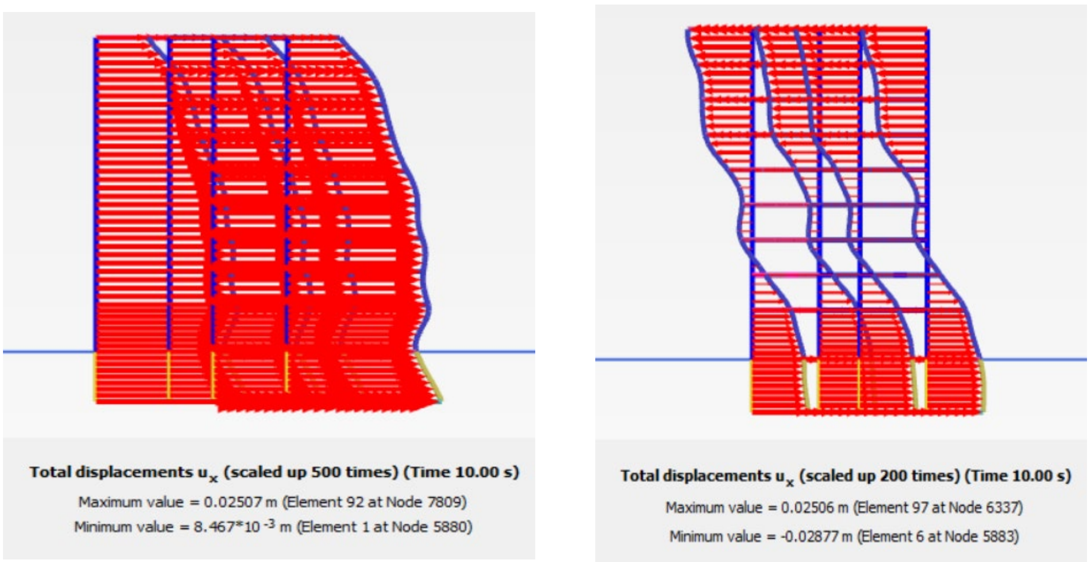
4 RESULTS AND DISCUSSION

To analyze the effectiveness of the software, validation calculations were performed based on real engineering-geological conditions and building projects in the Medeu district of Almaty. Computational models were considered using the Mohr-Coulomb and Hardening Soil Small models. The results of the calculations for normal force and moment are shown in the figure below. It can be observed that the results from the Mohr-Coulomb model almost agree with the analysis results. The linear elastoplastic Mohr-Coulomb model of ideal plasticity contains five input parameters: Young's modulus (E) and Poisson's ratio (ν) for soil elasticity, cohesion (c) for soil plasticity, the friction angle (φ), and the dilation angle (ψ). The Plaxis team recommends initially using this model to analyze existing problems. For each layer, an average constant stiffness is assessed. Due to this constant stiffness, calculations are generally completed relatively quickly, providing an initial estimate of deformations (**Merkulova et al., 2021**). On the other hand, the hardening soil model uses three types of stiffness (E50, Eur, Eoed), which depend on stress. E50 is resistant to the primary load, and its behavior at this level is highly nonlinear. Eur is the stiffness coefficient representing the stress path without load. Eoed is the oedometer modulus under the initial stress conditions. In addition to these stiffness values, cohesion (c), friction angle (φ), dilation angle (ψ), stress level (m), vur, K0nc, pref, and the initial conditions of the soil model are also used to determine the compaction behavior of the soil (**Jesus et al., 2015, Rafal et al., 2018**). It was found that the results of both models differed. Since the hardening soil model has additional parameters, it allows for more accurate and reliable results. In finite element analysis, appropriate stiffness values for the soil are required to provide a reasonable prediction of displacements. We observed that there are many differences between the two models. In the Mohr-Coulomb model, the deformed mesh or maximum displacement is 61.7×10^{-3} meters, as shown in Fig. 3. In the Hardening Soil Small model, the displacement of the deformed mesh is 52.3×10^{-3} meters, as shown in Fig. 4. Thus, we conclude that the mesh deformation or maximum displacement is smaller in the Hardening Soil Small model, which is associated with the stiffer behavior of the HS model (**Arjun et al., 2017**). Similarly, the total displacement of the building is 66.2 mm, as shown in Fig. 5, and 28.7 mm, as shown in Fig. 6, for the Mohr-Coulomb model and the Hardening Soil model, respectively. The negative sign indicates the direction (**Lina et al., 2018**).



(a) (b)

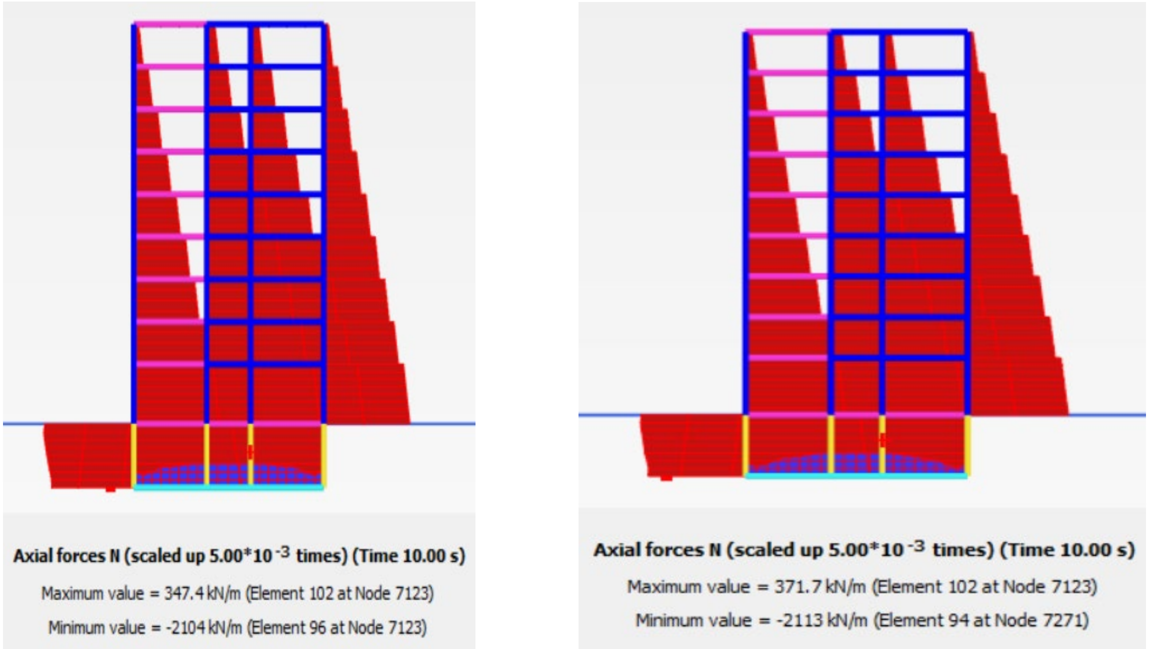
Figure 3 – (a) Deformed scheme by Mohr-Coulomb , (b) Deformed scheme by HSS (author's material).



(a) (b)

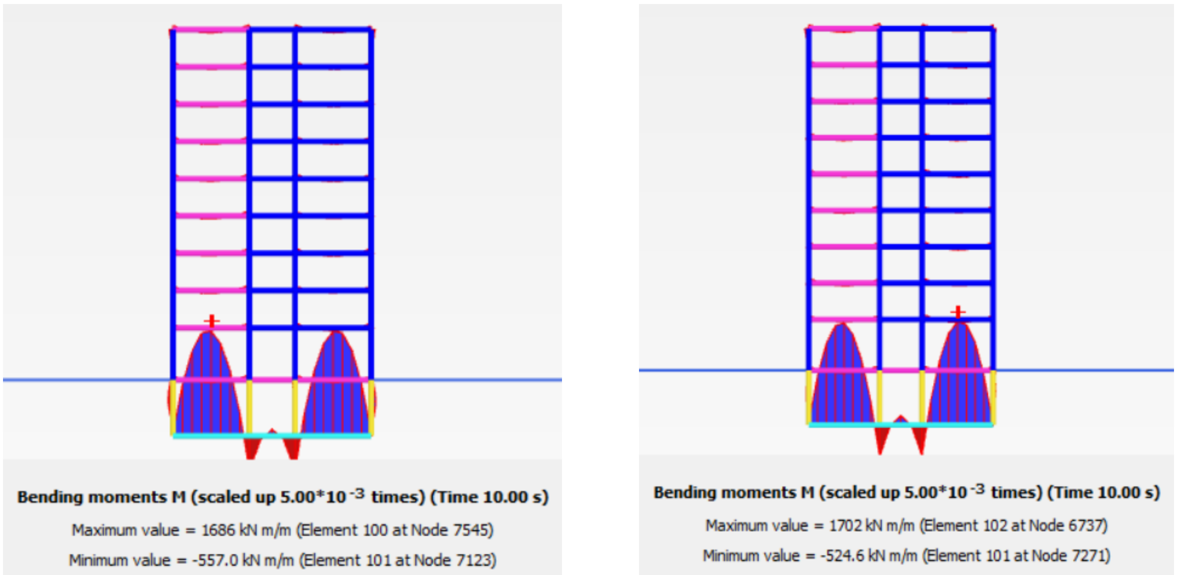
Figure 4 – (a) Mohr-Coulomb displacements, (б) HSS displacements (author's material).

We obtained higher stress values in the HSS model compared to the MC model. Additionally, several other results were found, such as the bending moment, which is 1686.0 kNm/m and 1702.0 kNm/m in the MC and HS models, respectively. The axial forces obtained in the HSS and MC models are -2104.0 kN/m and -2113.0 kN/m, respectively (the negative sign indicates the direction). All these values are shown in the figures, providing a more realistic comparison between both models (**Amjad et al., 2019, Endra et al., 2012**).



(a) (b)

Figure 5 – (a) Mohr-Coulomb axial force N, (b) axial force N by HSS (author's material).



(a) (b)

Figure 6 – (a) Bending moment M by Mohr-Coulomb, (b) Bending moment M by HSS (author's material).

To determine the maximum displacements, a point was selected for each floor. The graph shows a sharp increase observed on the sixth floor. From this, it can be concluded that the difference in maximum displacement is 33 percent (**Charles et al., 2021**).

Table 2
Maximum Floor Movements by Floor Level for Different Soil Models

Floors	Maximum floor movements, mm										
	basement	1	2	3	4	5	6	7	8	9	10
Mora-Coulomb	5,05	6,55	10,5	13,5	17,24	23,43	32,34	40,20	44,67	53,81	58,92
HSS	5,18	5,97	5,36	8,41	11,72	17,64	26,22	29,5	32,92	31,71	39,32

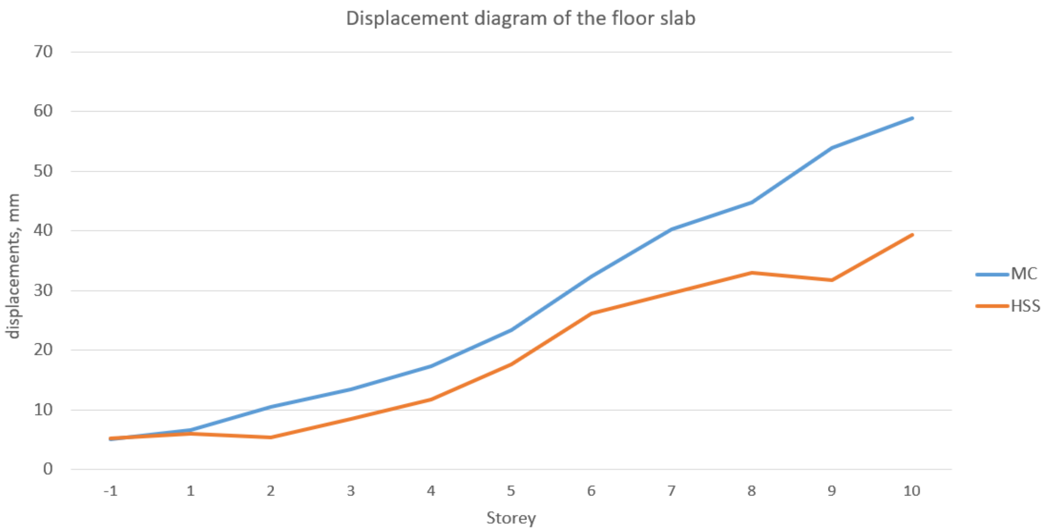


Figure 7 – Displacement diagram of the floor slab (author's material).

5 CONCLUSIONS

Ground movement under seismic impact on buildings is smaller in the HSS model compared to the MC model, which is due to differences in the unloading behavior of both models.

Stress-dependent stiffness in the behavioral model and the difference in stiffness between initial loading and unloading/reloading are critical aspects of modeling when discussing seismic impacts and play a significant role in predicting ground oscillations. Therefore, it is recommended that analysts use advanced models for seismic impact simulations.

Structural forces, such as axial and shear forces in the walls, are higher in the HSS model compared to the MC model. Similarly, stress values are greater in the HSS model than in the MC model, and the factor of safety in the HSS model is also higher than in the MC model. Practical examples have proven that for different types of soil models under seismic conditions, where unloading behavior of the soil is crucial, the Hardening Soil Small (HSS) model provides more realistic and accurate results than the Mohr-Coulomb (MC) model (**Semet, 2023**).

REFERENCES

1. **Sokolova, O.V.** (2014). The selection of soil models parameters in Plaxis 2D. Magazine of Civil Engineering 48(4). https://engstroy.spbstu.ru/en/article/2014.48.2/

2. **Schanz, T., Vermeer, P. A., Bonnier, P. G.** (1999). The hardening soil model formulation and verification. In book: Beyond 2000 in Computational Geotechnics (pp.281-296). https://www.taylorfrancis.com/chapters/edit/10.1201/9781315138206-27/hardening-soil-model-formulation-verification-schanz-vermeer-bonnier
3. **Benz, T., Schwab, R. & Vermeer, P.** (2009). Small-strain stiffness in geotechnical analyses. Bautechnik 86(S1):16-27. https://doi.org/10.1002/bate.200910038
4. **Alekseev, A.V., Yovlev, G.A.** (2019). Adaptation of the Hardening Soil model for geotechnical engineering conditions of St. Petersburg. Mining International and Analytical Bulletin 2019;4:75-87. https://www.giab-online.ru/files/Data/2019/4/75_87_4_2019.pdf
5. **Vakili, K.N., Barciaga, T., Lavasan, A.A., Schanz, T.** (2013). A practical approach to constitutive models for the analysis of geotechnical problems. Conference: The Third International Symposium on Computational Geomechanics (ComGeo III)At: Krakow, PolandVolume:1 URL:https://www.researchgate.net/publication/266563320_A_PRACTICAL_APPROACH_TO_CONSTITUTIVE_MODELS_FOR_THE_ANALYSIS_OF_GEOTECHNICAL_PROBLEMS
6. **Brinkgreve, R.B.J., Engin, E. & Swolfs, W.M.** (2011). Material models manual, Plaxis 2D. Plaxis bv, Delft, Netherlands. URL: https://communities.bentley.com/cfs-file/__key/communityserver-wikis-components-files/00-00-00-05-58/0118.PLAXIS3DCE_2D00_V20.02_2D00_3_2D00_Material_2D00_Models.pdf
7. **Merkulova, A.D., Zubarev, V.S.** (2021). Hardening soil: practical experience in applying the results of geotechnical engineering surveys. URL:https://mosproekt3.ru/wp-content/uploads/2021/10/metro-i-tonneli-oktyabr-2021.pdf
8. **Jesus, F.R., Luis, M.R.** (2015). Application of an advanced soil constitutive model to the study of railway vibration in tunnels through 2D numerical models. A real case in Madrid (Spain). Revista de la construcción 14(3):55-63. http://dx.doi.org/10.4067/S0718-915X2015000300007
9. **Rafal, F.O., Andrej, T.** (2018). The hardening soil model – practical guidebook. URL:https://www.zsoil.com/zsoil_manual_2018/Rep-HS-model.pdf
10. **Arjun, G., Ankit, S.** (2017). Comparison of different soil models for excavation using retaining walls. IJCE Journal Volume 4 Issue 3. https://doi.org/10.14445/23488352/IJCE-V4I3P110
11. **Lina, J., Yehya, T., Fadi, H.C., Yasser, E.** (2018). Effect of soil – Structure interaction constitutive models on dynamic response of multi-storey buildings. Journal of Engineering Science and Technology Review 11(3):56-60. http://www.jestr.org/downloads/Volume11Issue3/fulltext81132018.pdf
12. **Amjad, H.B., Shahnawaz, Z., Ghulam, S.B., Muhammad, A.Z., Riaz, B., Bashir, A.M., Muhammad, M.B.** (2019). Mohr-Coulomb and hardening soil model comparison of the settlement of an embankment dam. Engineering, Technology and Applied Science Research 9(5):4654-4658. https://doi.org/10.48084/etasr.3034.
13. **Endra, S., Dayu, A.** (2012). Settlement of a full trial embankment on peat in Kalimantan: Field measurements and finite element simulations. Jurnal Teknik Sipil 19(3):249. https://doi.org/10.5614/jts.2012.19.3.6
14. **Charles, C.L.C., Derek, S.M.C., Frankie, L.C.L., Julian, S.H.K., Alex, C.O.L.** (2021). Back analysis of two deep excavations of Hong Kong Using the Mohr-Coulomb Model with linear elasticity and the hardening soil model. Vol. 7, Issue 1, p.137-163. http://dx.doi.org/10.4417/IJGCH-07-01-07
15. **Semet, C.** (2023). Comparison Mohr-Coulomb and Hardening soil ,models numerical estimation of ground surface settlement caused by tunneling. Journal of the Institute of Science and Technology 7(4):95-102. https://dergipark.org.tr/tr/download/article-file/419657