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Cyclic properties of sand-clay mixtures at low confining stresses

Propriétés cycliques des mélanges sable-argile à faibles contraintes de confinement

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ABSTRACT: Small strains and shear stresses induced by railroad vibration, dynamic compaction, or earthquakes can cause strength degradation, pore pressure build-up, and accumulation of strains at large number of load cycles. In general, strength degradation and pore water pressure build-up are correlated with the plasticity index and thus the content of fine particles, meaning that a threshold for strength degradation will be lower for sands than for silty and clayey sands. Confining stresses play a significant role in soils shear behaviour. Fully saturated soil at low confining stresses is likely to have a significant strength reduction compared to the soil at higher confining stresses if loaded to the same number of cycles. This is very important for slopes that are prone to shallow sliding. This paper presents the test results of an artificial mixtures of sand and kaoline used for a small-scale physical model of slope subjected to cyclic loading. Mixtures are tested using cyclic triaxial apparatus under undrained condition at low confining stresses. The results show that the sand-clay mixture with 15% of kaoline powder exhibit larger pore water pressure than the mixtures with lower percentage of kaoline.

RÉSUMÉ: De petites déformations et contraintes de cisaillement induites par les vibrations ferroviaires, le compactage dynamique ou les tremblements de terre peuvent provoquer une dégradation de la résistance, une augmentation de la pression interstitielle et une accumulation de déformations sur un grand nombre de cycles. En général, la dégradation de la résistance et l'accumulation de pression interstitielle sont corrélées à l'indice de plasticité et donc à la teneur en particules fines, ce qui signifie qu'un seuil de dégradation de la résistance sera plus bas pour les sables que pour les sables limoneux et argileux. Les contraintes de confinement jouent un rôle important dans le comportement au cisaillement des sols. Un sol entièrement saturé à de faibles contraintes de confinement est susceptible de présenter une réduction significative de sa résistance par rapport au sol soumis à des contraintes de confinement plus élevées s'il est chargé selon le même nombre de cycles. Ceci est très important pour les pentes sujettes à des glissements peu profonds. Cet article présente les résultats d'un mélange artificiel de sable et de kaoline utilisé pour un modèle physique à petite échelle de pente soumise à un chargement cyclique. Les mélanges sont testés à l'aide d'un appareil triaxial cyclique dans des conditions non drainées et à faibles contraintes de confinement. Les résultats montrent que le mélange sable-argile contenant 15 % de poudre de kaoline présente une pression d'eau interstitielle plus élevée que les mélanges contenant un pourcentage plus faible de poudre de kaoline.

Keywords: Low confining stress; cyclic soil behavior; sand-clay mixtures, cyclic triaxial test, strain-controlled test.

1 INTRODUCTION

The study of sand-clay and sand-silt mixtures has a rich history in both monotonic and cyclic soil behaviour. Past investigations (e.g., (Thevanayagam, 1998), (Yamamuro et al., 1999), (Seed, 2010)) have extensively explored this area, and the area knowledgebase still continues to be expanded (e.g., (Othman et al., 2022), (Ranga Swamy et al., 2021), (Lü et al., 2022)). Understanding the mechanics of interparticle contacts in silty and clayey sandy soils is a challenging endeavour due to the presence of clay minerals. Benessalah et al. (2021) examined the intergranular void ratio and the undrained monotonic behaviour of sand containing low plasticity fine particles. Their findings revealed that the fines' content exerts a substantial influence on the instability stress, as defined by the undrained instability state (Murthy et al., 2007). Another significant contribution was made by Nougar et al. (2021), who conducted a thorough investigation into the impact of fines content on the mechanical behaviour of mixtures. Their research highlights a clear trend: as the fines content increases, the strength of these mixtures decreases. The work of Dafalla et al. (2020) pointed out that higher fines content leads to reduced dilatation in mixtures. Furthermore, Akhila et al. (2019) observed that non-plastic silty sands and loamy sands with a low plasticity index (up to 15) exhibit greater susceptibility to liquefaction than fine sands. Wu et al. (2019) provided insightful documentation on the behaviour of artificial sand-clay mixtures, revealing a complex interplay of transitional and secondary compression behaviour. This response is significantly influenced by the creep of the fine fraction, emphasizing the material's complex nature. Balreaddy et al. (2021) unveiled that cyclic strength decreases with an increase in fines content by up to 20%. Surprisingly, with further increase in the proportion of fines, cyclic strength experiences an upswing, indicating that fines content becomes the predominant factor in controlling soil behaviour. Karim and Alam (2014) conducted a series of cyclic triaxial tests on specimens with a 20% silt content. Their study revealed that the rate of pore pressure generation initially rises with increased silt content, only to begin decreasing afterwards. Cyclic resistance experiences a decrease until a silt content limit of approximately 35% is reached, after which it stabilizes. These studies collectively contribute to the understanding of the complex behaviour of mixtures involving sand and clay material and their implications for geotechnical engineering. Another important role in the soil behaviour is govern by the confining pressure. According to White (2020) the secant shear modulus, denoted as Gs, was observed to decline as the number of cycles increased and as the effective stress decreased. Kumar et al. (2017) observed that the specimen exposed to lower levels of effective stresses (50 kPa) exhibited a higher damping ratio compared to the specimens exposed to higher levels of effective stresses (100 and 150 kPa). This difference can be attributed to the relatively high stiffness caused by the constraints on the specimen. In their investigation, Shaoli et al. (2003) highlighted that clean sand has a substantial dilating behavior at lower effective stresses. As a result, compared to behavior at high effective stresses, clean sand is more resilient under low effective stresses. The influence of clay content on the soil behaviour under low confining stress has to be examined further.

As part of two research projects, “Laboratory research of static and cyclic behavior at landslide activation (uniri-tehnic-18-113),” funded by the University of Rijeka, and “Physical modelling of landslide remediation constructions’ behavior under static and seismic actions (ModLandRemSS, IP-2018-01-1503),” funded by the Croatian Science Foundation, a series of physical model tests was conducted on small-scale slopes subjected to dynamic loading using a shaking table platform.

To gain a comprehensive understanding of the material’s response used in small-scale slope models, a series of cyclic triaxial tests were carried out on the artificial sand-clay mixtures used for the construction of the small-scale slope models. This paper focuses on presenting the preliminary findings derived from undrained, strain-controlled cyclic triaxial tests conducted on these mixtures. The results provide valuable insights into the material’s behaviour under cyclic loading conditions, which is essential for the assessment and understanding of slope stability subjected to cyclic loading.

2 METHODOLOGY

2.1 Material properties and specimen preparation

Industrial kaoline powder and homogeneous Drava River sand are combined to create artificial sand-clay mixtures. Artificial mixtures are named based on the mass ratio of sand (S) and kaoilne (K). The characteristics of Drava River sand (herein SK0) and kaoline powder (herein SK100) are well documented (Jagodnik & Arbanas, 2022; Marušić & Jagodnik, 2023; Pajalić et al., 2021). A mixture containing 10% kaoline powder per mass ratio (herein SK10) and a mixture containing 15% kaolinite powder per mass ratio (herein SK15) are prepared and tested in the dynamic triaxial apparatus. Physical properties of material are summarized in Table 1.

Using the undercompaction method for specimen preparation proposed by Ladd (Ladd, 1978), specimens were prepared with 5% undercompaction. The method's positive and negative aspects are documented by (Frost & Park, 2003; Jagodnik & Arbanas, 2022; Kodicherla et al., 2018; Raghunandan et al., 2012). Before the saturation stage, each specimen was percolated with CO_2, followed with water percolation as well. Upon finished saturation (B value above 0.95), specimens were isotropically consolidated at effective confining stress of 25 kPa or 50 kPa.

2.2 Testing procedure

Undrained strain-controlled cyclic triaxial tests were performed using dynamic triaxial apparatus manufactured by Controls Group Ltd. (Controls Group, 2023). Tests were performed on the previously defined soil mixtures to determine the cyclic behaviour, the strength degradation, and the change of pore water pressure ratio, at low confining stresses.

Table 1. Physical properties of the used specimens

Property	SK0	SK10	SK15	SK100
Specific gravity, Gs	2.70	2.69	2.67	2.60
D10 [mm]	0.183	0.054	0.0045	N/A
D60 [mm]	0.320	0.307	0.303	N/A
Uniformity coef-ficient, Cu [-]	1.749	5.685	67.333	N/A
Curvature coef-ficient, Cc [-]	0.959	2.893	31.123	N/A
Minimum void ratio, e_{min} [-]	0.547	0.596	0.640	0.849
Maximum void ratio, e_{max} [-]	0.856	1.022	1.128	1.636
Plastic limit [%]	N/A	5.8	9.6	21.6
Liquid limit [%]	N/A	17.9	17.9	48.3
Percent of clay particles ($\leq 0.002mm$) [%]	0	1	1.5	10

N/A – non applicable

Strain-controlled tests were performed in nine straining stages, each having a consolidation stage between (e.g. (Jagodnik & Arbanas, 2022; Vucetic et al., 2021)). Table 2 shows the corresponding cyclic axial deformation for each straining stage and equivalent shear strain. The specimens were tested in an undrained condition hence the shear strain can be calculated using :

$$\gamma = 1.5 \cdot \varepsilon_a \quad (1)$$

Table 2. Cyclic testing stages and equivalent cyclic axial and cyclic shear strain.

Testing stage	Cyclic Axial Strain $\varepsilon_{a,c}$ (%)	Cyclic Shear Strain $\gamma_{a,c}$ (%)
1	0.0033	0.005
2	0.005	0.0075
3	0.0067	0.01
4	0.013	0.02
5	0.033	0.05
6	0.05	0.075
7	0.067	0.1
8	0.133	0.2
9	0.333	0.5

3 RESULTS AND DISCUSSION

In the following section, the results of strain-controlled tests are summarized. The influence of low confining stresses on the artificial mixtures are presented with the strength degradation and normalized pore water pressure response build-up. In cyclic simple shear, the degradation index in strain-controlled tests can be calculated as a ratio of the shear stress in current loading cycle with respect to the shear stress at first cycle (Mortezaie & Vucetic, 2013). Contrary to simple shear, in cyclic triaxial test the cyclic loop is nonsymmetric so the average value of secant shear modulus have to be taken into consideration (e.g., (Jagodnik & Arbanas, 2022; Kumar et al., 2017)). In this case, degradation index is calculated using the as:

$$\delta_N = \frac{|q_{C,N}| + |q_{E,N}|}{|q_{C,1}| + |q_{E,1}|} \quad (2)$$

where $q_{C,N}$ and $q_{E,N}$ are the maximum and minimum deviatoric stress in compression and extension, respectively, at Nth cycle and $q_{C,1}$ and $q_{E,1}$ are the maximum and minimum deviatoric stress in compression and extension, respectively, in the first cycle.

Deviatoric stress is calculated as a difference in effective triaxial stresses:

$$q = \sigma_1' - \sigma_3' \quad (3)$$

where σ_1' is the vertical effective stress and σ_3' is radial effective stress.

Normalized pore water pressure ratio is calculated as a change of pore water pressure during loading cycle with respect to confining effective stress:

$$r_u = \frac{\Delta u}{\sigma_c'} \quad (4)$$

where Δu is the change of pore water pressure during the test and σ_c' is the effective confining stress which corresponds to cell pressure σ_3'.

Figure 1 present the degradation (δ_N) of artificial mixtures "SK10" and "SK15" at effective confining stresses 25 kPa and 50 kPa, respectively, with respect to the number of cycles (N).

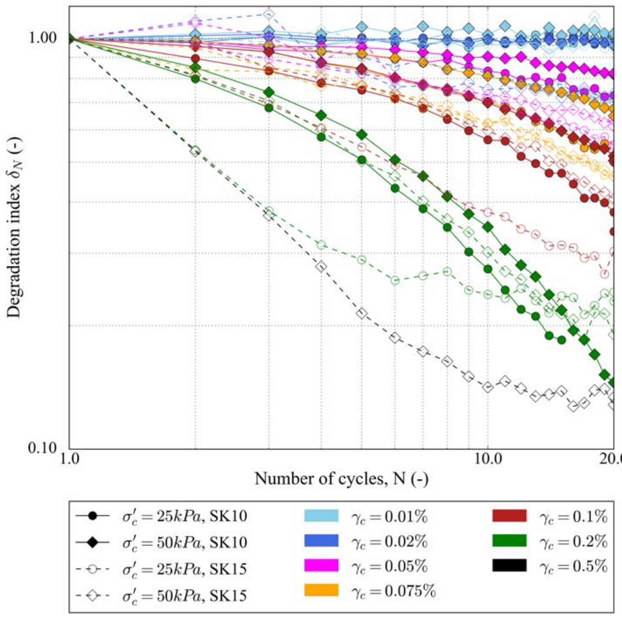

Figure 1. Degradation index change with number of cycles.

The maximum level of cyclic shear strain reached by the specimen labelled as "SK10" was 0.2% for both 25kPa and 50kPa confining stress. When subjected to a higher level of confining pressure, the specimen withstands 20 load cycles, while at 25 kPa confining stress, it only withstands 15 cycles. The decline in performance of the "SK10" specimen exhibits a somewhat non-linear nature, which can be attributed to the relatively low clay content present in the sand-clay matrix. Contrarily, the specimen labelled as "SK15" exhibits an almost linear decline in performance up to a relative cyclic shear strain of 0.2% under a confining stress of 25 kPa and 0.5% under a confining stress of 50 kPa. Degradation is initiated after reaching a cyclic shear strain of 0.02%, in contrast to the "SK10" specimen where degradation initiates upon reaching 0.05%.

Figure 2 presents the relation between the degradation index (δ_N), as defined by equation (2), and the normalized pore water pressure ratio (r_u), as defined by equation (4). Additionally, it illustrates the impact of effective confining stress on the degradation index.

A higher confining pressure allows the soil to withstand more shear cycles before reaching the same degradation index and pore water pressure ratio. The nonlinearity of the curves indicates the influence of the sand grain, which differs from the results of specimen "SK15" where the degradation is almost linear in relation to the pore pressure ratio.

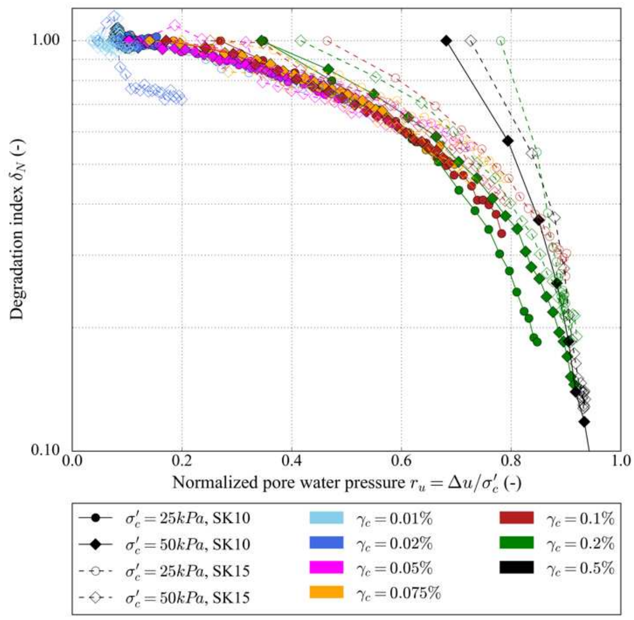

Figure 2. Degradation index change with normalized pore water pressure.

4 CONCLUDING REMARKS

A mixture of sand and kaoline clay in mass ratios of 10% and 15% were subjected to an undrained cyclic strain-control triaxial tests at low confining stresses.

At lower levels of confining stress, specimen containing 10% clay exhibit a smaller degradation index compared to those with a clay content of 15% for a range of cyclic shear strain up to 0.1%. The average degradation index at 10th cycle is 0.6. Specimen with 15% clay content at 25kPa showed smaller degradation index at 10th cycle (around 0.4), which means that almost 60% of strength was lost during previous loading cycles at cyclic shear strain of 0.1%.

The degradation of specimen containing 10% of the clay fraction exhibits a nonlinear behaviour once higher cyclic shear strain is applied. The specimens with 15% of clay display an almost linear behaviour until the interparticle connections are disrupted, resulting in a manifestation of high nonlinearity in the degradation index. The normalized pore water pressure ratio (r_u) experiences a rapid increase when the r_u gets the value of 0.6. Taking for example cyclic shear strain of 0.2%, the mixtures with 10% of kaoline can withstand from 3 to 5 cycles of loading, depending on the confining stress, until the r_u value of 0.6 is reached. For the mixtures containing 15% of kaoline, the role of confining stress is significant. At the confining stress of 25 kPa, r_u value is around 0.78 in the first cycle, while at the 50 kPa confining stress, it takes 2.5 cycles to reach the $r_u$value of 0.6. Higher cyclic shear strain was only possible under the effective stress of 50 kPa, generating the normalized pore water pressure r_u in the first cycle of around 0.7, followed with the rapid degradation.

The executed experimental findings have revealed that the presence of 15% of clay particles within a specimen exerts a greater effect on the formation of pore pressure compared to a specimen composed of 10% of clay particles, under the same magnitude of relative cyclic shear deformation.

According to the presented test results, a slope under cyclic excitation such as earthquake, and in undrained condition, can exhibit large strength degradation if the clay content is lower than 20%.

The results of the conducted experiments will be important in the calibration of numerical models using the results of the experiments in the next phase of the research.

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REFERENCES

Akhila, M., Rangaswamy, K., & Sankar, N. (2019). Liquefaction susceptibility of silty sands and low plastic clay soils. International Journal of Geotechnical Earthquake Engineering, 10(2), 1–17. https://doi.org/10.4018/IJGEE.2019070101.

Balreddy, M. S., Dinesh, S. V., & Sitharam, T. G. (2016). Influence of sand and low plasticity clay mixtures on the liquefaction and postliquefaction behavior. Japanese Geotechnical Society Special Publication, 2(21), 806–810. https://doi.org/10.3208/jgssp.IND-10.

Balreddy, M. S., Dinesh, S. V., & Sitharam, T. G. (2021). Liquefaction behavior of low to medium plasticity sand-fines mixtures (pp. 181–191). https://doi.org/10.1007/978-981-33-4001-5_17.

Benessalah, I., Arab, A., & Meziane, E.-H. (2021). Intergranular void ratio and undrained monotonic behavior of Chlef sand containing low plastic fines. Acta Mechanica, 232(4), 1621–1640. https://doi.org/10.1007/s00707-020-02923-0.

Controls Group. (2023). Dynamic triaxial tests system—DYNATRIAX, Soil mechanics testing equipment, Controls. https://controls-group.com/product/dynamic-triaxial-system-dynatriax-ems-controls/.

Dafalla, M., Shaker, A., Elkady, T., Almajed, A., & Al-Shamrani, M. (2020). Shear strength characteristics of a sand clay liner. Scientific Reports, 10(1), 18226. https://doi.org/10.1038/s41598-020-75188-1.

Frost, J., & Park, J.-Y. (2003). A Critical Assessment of the Moist Tamping Technique. Geotechnical Testing Journal, 26(1), 9850. https://doi.org/10.1520/GTJ11108J.

Jagodnik, V., & Arbanas, Ž. (2022). Cyclic Behaviour of Uniform Sand in Drained and Undrained Conditions at Low Confining Stress in Small-Scale Landslide Model. Sustainability, 14(19), 12797. https://doi.org/10.3390/su141912797.

Karim, M. E., & Alam, Md. J. (2014). Effect of non-plastic silt content on the liquefaction behavior of Sand–Silt mixture. Soil Dynamics and Earthquake Engineering, 65, 142–150. https://doi.org/10.1016/j.soildyn.2014.06.010.

Kodicherla, S. P. K., Gong, G., Fan, L., Moy, C. K. S., & He, J. (2018). Effects of preparation methods on inherent fabric anisotropy and packing density of reconstituted sand. Cogent Engineering, 5(1), 1533363. https://doi.org/10.1080/23311916.2018.1533363.

Kumar, S. S., Krishna, A. M., & Dey, A. (2017). Evaluation of dynamic properties of sandy soil at high cyclic strains. Soil Dynamics and Earthquake Engineering, 99, 157–167. https://doi.org/10.1016/j.soildyn.2017.05.016.

Ladd, R. S. (1978). Preparing test specimens using under compaction. Geotechnical Testing Journal, 1(1), 16–23. https://doi.org/10.1520/GTJ10364J.

Lü, X., Xue, D., Zhang, B., & Zhong, Q. (2022). Experimental Studies and Constitutive Modeling of Static Liquefaction Instability in Sand–Clay Mixtures. International Journal of Geomechanics, 22(9), 04022149. https://doi.org/10.1061/(ASCE)GM.1943-5622.0002472.

Marušić, D., & Jagodnik, V. (2023). Determination of the Atterberg Limits Using a Fall Cone Device On Low Plasticity Silty Sands. Rudarsko-Geološko-Naftni Zbornik, 38(3), 133–145. https://doi.org/10.17794/rgn.2023.3.11.

Mortezaie, A. R., & Vucetic, M. (2013). Effect of Frequency and Vertical Stress on Cyclic Degradation and Pore Water Pressure in Clay in the NGI Simple Shear Device. Journal of Geotechnical and Geoenvironmental Engineering, 139(10), 1727–1737. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000922

Murthy, T. G., Loukidis, D., Carraro, J. A. H., Prezzi, M., & Salgado, R. (2007). Undrained monotonic response of clean and silty sands. Géotechnique, 57(3), 273–288. https://doi.org/10.1680/geot.2007.57.3.273.

Nougar, B., Brahimi, A., Bouri, D. E., Arab, A., & Benessalah, I. (2021). Laboratory investigation into the effect of fines plasticity on the mechanical behavior of Sand/Fines mixtures. Transportation Infrastructure Geotechnology, 8(3), 438–451. https://doi.org/10.1007/s40515-020-00144-5.

Othman, B. A., Marto, A., Uzuoka, R., Ueda, K., & Satar, M. H. M. (2022). Liquefaction Resistance of Sand-Kaolin Mixtures: Effect of Sand Sizes. IOP Conference

Series: Earth and Environmental Science, 1103(1), 012026. https://doi.org/10.1088/1755-1315/1103/1/012026.
Pajalić, S., Peranić, J., Maksimović, S., Čeh, N., Jagodnik, V., & Arbanas, Ž. (2021). Monitoring and data analysis in small-scale landslide physical model. Applied Sciences (Switzerland), 11(11). https://doi.org/10.3390/app11115040.
Raghunandan, M. E., Juneja, A., & Hsiung, B. C. B. (2012). Preparation of reconstituted sand samples in the laboratory. International Journal of Geotechnical Engineering, 6(1), 125–131. https://doi.org/10.3328/IJGE.2012.06.01.125-131.
Ranga Swamy, K., Akhila, M., & Sankar, N. (2021). Effects of fines content and plasticity on liquefaction resistance of sands. Proceedings of the Institution of Civil Engineers - Geotechnical Engineering, 174(6), 697–706. https://doi.org/10.1680/jgeen.19.00270.
Seed, R. B. (2010). Soil Liquefaction During Earthquakes (Issue UCB/GT-2010/01) [Technical review and comments]. University of California at Berkeley. https://vulcanhammernet.files.wordpress.com/2017/01/liquefactionreview.pdf.
Shaoli, Y., Sandven, R., & Grande, L. (2003). Liquefaction of sand under low confining pressure. Journal of Ocean University of Qingdao, 2(2), 207. https://doi.org/10.1007/s11802-003-0053-9.
Thevanayagam, S. (1998). Effect of Fines and Confining Stress on Undrained Shear Strength of Silty Sands. Journal of Geotechnical and Geoenvironmental Engineering, 124(6), 479–491. https://doi.org/10.1061/(ASCE)1090-0241(1998)124:6(479)..
Vucetic, M., Thangavel, H., & Ahmadreza Mortezaie. (2021). Cyclic secant shear modulus and pore water pressure change in sands at small cyclic strains. Journal of Geotechnical and Geoenvironmental Engineering, 147(5), 04021018. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002490.
White, J. R. F. (2020). A Laboratory Investigation Into the Behaviour of Sand at Low Confining Stresses. University of Oxford. https://books.google.hr/books?id=fG9gzgEACAAJ.
Wu, Z., Deng, Y., Cui, Y., Chen, Y., Wang, Q., & Feng, Q. (2019). Investigations on secondary compression behaviours of artificial soft sand-clay mixtures. Soils and Foundations, 59(2), 326–336. https://doi.org/10.1016/j.sandf.2018.11.008.
Yamamuro, J. A., Covert, K. M., & Lade, P. V. (1999). Static and cyclic liquefaction of silty sands. In P. V. Lade & J. A. Yamamuro (Eds.), Physics and Mechanics of Soil Liquefaction (1st ed., pp. 55–65). Routledge. https://doi.org/10.1201/9780203743317-5.