An Analytical Parametric Study on Behaviour of Flexible Raft Foundation

Pritam Sinha[1] Ram Wanare[2] Parishi Dalal[3] and Kannan K. R Iyer[4]

[1]Formerly Post Graduate Student, Department of Civil Engineering, Institute of Infrastructure Technology, Research and Management, Ahmedabad-380026, India, pritam.sinha.17mc@iitram.ac.in

[2]Research Scholar, Department of Civil Engineering, Institute of Infrastructure Technology, Research and Management, Ahmedabad-380026, India, ram.wanare.19pc@iitram.ac.in

[3]Post Graduate Student, Department of Civil Engineering, Institute of Infrastructure Technology, Research and Management, Ahmedabad-380026, India, parishi.dalal.18mc@iitram.ac.in

[4]Assistant Professor, Department of Civil Engineering, Institute of Infrastructure Technology, Research and Management, Ahmedabad-380026, India, kannaniyer@iitram.ac.in

Abstract. The understanding of soil-foundation-structure interaction is important for design of flexible raft foundation. For flexible foundation, the behaviour would be influenced by the loading as well as the foundation and soil parameters. The present study attempts to understand the influence of the parameters such as meshing size, loading intensity, magnitude of modulus of subgrade reaction (K_s) and raft thickness on base pressure and settlement of flexible raft foundation using STAAD Pro. A symmetrical multistoreyed building with 25 columns along with raft foundation has been modeled. The building height is varied as 3-storeyed, 6-storeyed and 10-storeyed to simulate different loading intensity and thickness is varied as 0.5m and 0.9m to understand effect of raft rigidity. K_s values of 2000 kN/m^3 and 12000 kN/m^3 have been considered for the study. Study concludes that 0.5m mesh size be utilized for all practical foundation modeling purposes. The effect of K_s on base pressure and settlement variation is more prominent as compared thickness of raft foundation. Further, the base pressure and settlement increases linearly with increase in storey height. The study presents useful guidelines for foundation engineers for design of flexible raft foundation.

Keywords: flexible raft, foundation, soil-structure interaction, base pressure, settlement

1 Introduction

1.1 Soil structure interaction

Behavior of structure and its foundation depends on soil and the response of soil to pressure experienced from foundation. Hence understanding the soil-structure interaction (SSI) becomes important for proper and optimum design of foundation. Soil-structure interaction can be understood by defining the appropriate value of modulus of subgrade reaction, which can be defined as the foundation pressure required to cause unit settlement of soil (Terzaghi 1955). Soil-structure interaction begins at the initial phase of construction and equilibrium depending on the variable factors can be achieved after some period. Winkler (1867) was the first researcher to address the parameter, modulus of subgrade reaction (K_s), which is an important parameter for soil-structure interaction studies (Terzaghi 1955). It has also been stated that soil can be represented as infinite number of springs at the interface between soil and foundation, and the stiffness of the spring can be defined as K_s. Terzaghi (1955) has presented a detailed review of modulus of subgrade reaction, K_s which represents deformation characteristics and depends on loaded area which follows Hooks law. According to Larkela et al. (2013), K_s is influenced by pseudo elastic property and it is not a fundamental property of soil. Also it depends on elastic properties of soil, foundation dimensions, stiffness of foundation and other factors such as depth of foundation below ground surface, compressible soil layer thickness (Aristorenas and Gomez 2014, Teli et al. 2019)

Horvath (1983) assumed that modulus of elasticity (E) is not constant throughout the depth but it varies; hence affecting K_s. Although K_s has been noted to have less effect in the structural design of foundation, it has an immense effect on the contact pressure distribution and settlement, hence affects the foundation base area. Incidentally K_s is also dependent on the dimensions of the foundation (Terzaghi 1955). Eimarakbi and Budkowska (2001) reported that K_s obtained for pile foundation by static method has considerable amount of inaccuracy due to discrete modelling based on Winkler approach and highlighted the dependency of K_s on pile width. K_s directly affects the settlement of the foundation and the settlement distribution depends on other factors such as rigidity of foundation, loading intensity and location and relative stiffness of foundation and soil. As per Briaud (2001), modulus of subgrade reaction (K_s) is closely related to the soil properties and degree of compaction. A densely packed soil has high K_s, however it also depends on the porosity and dry density. Soil with same dry density but different micro-structure will have different values of K_s. In fine-grained soil, less water content works as a binder (adhesion) due to suction forces and this adhesion will increase K_s as it develops adhesion effect due to capillary induced suction. But for coarse grained soil K_s increases with increasing water content till a specific limit (Briaud, 2001). The stress history of soil also affects K_s and it has been reported that over consolidated soil has higher K_s than the normally consolidated soil. K_s is inversely proportional to strain level in soil, and higher strain rate enhances the stiffness of the soil hence resulting in higher K_s. For cohesionless soil, K_s has been reported to increase with increase in confining pressure as the soil depth increases.

Barounis et al. (2009) used unconfined compression test (UCS) to evaluate K_s and it has been noted that the value of K_s evaluated from this test is very less due to the absence of the confining pressure.

Worku (2009) based on their study have reported that Winkler's model, based on the assumption that soil which is represented by spring of certain stiffness below the loaded area is inappropriate, but this approximation can be overcome by appropriate calculation of shear stress of the sub grade soil. Aristorenas and Gomez (2014) have noted that K_s is not a soil property but the contact pressure of foundation which causes deflection in the soil. It depends on elastic properties of soil such as elastic modulus of soil (E_s) and Poissons ratio (ν_s), foundation plan dimensions, foundation stiffness and other indirect factors like depth of foundation below ground surface and compressible soil layer thickness. The various factors affecting modulus of subgrade reaction (K_s) as per Briaud (2001) and Dey et al. (2011) are packing density and particle arrangement; water content; stress history; confining effect; cyclic loading; type and rigidity of foundation. Although earlier studies have attempted to understand the influence of various factors on modulus of subgrade reaction (K_s), their influence on foundation design parameters such as base pressure and settlement needs further studies. The present study attempts to address these aspects.

1.2 Finite element analysis of foundation using STAAD Pro.

Present study attempts to understand the effect of various factors such as rigidity of foundation, variation in loading intensity and variation in magnitude of modulus of subgrade reaction, K_s, below foundation. Although the soil is a continuum under the structure but is a reasonable assumption to consider soil as discrete springs supporting the foundation based on Winkler's hypothesis. STAAD Pro V8i. (a popular software for soil-structure interaction studies) is utilized in the study for finite element analysis of foundation. Soil can be represented as spring with stiffness defined as per the value of K_s in STAAD Pro. In this study, 12 design alternatives have been studied based on variation of parameters such as mesh size of foundation elements modelled (0.25m, 0.5m and 1m mesh size), loading intensity (3-storey, 6-storey and 10-storeyed building loading), K_s values (2000 kN/m^3 and 12000 kN/m^3) and foundation thickness (0.5m and 0.9m). The different foundation design parameters such as base pressure and settlement has been obtained and compared for these alternatives. When a foundation is designed as flexible foundation, it is usually acceptable to utilize Winkler's model of representing soil as discrete spring below foundation. In STAAD Pro, the continuity of foundation below the soil springs helps in distribution of load to the springs as per the relative stiffness of raft and spring (soil). Hence the approach used in STAAD Pro can be considered as modified Winkler approach. In present study a Multi-storey building design has been adopted and plate elements (element suitable for flexible foundation) has been used to model raft foundation in STAAD Pro. The supports have been assigned with vertical spring stiffness values in the model. Vertical loads (Dead load and live load) on the building were applied as per IS: 875 Part- I. For simplicity, only vertical loads have been considered in the study. The details of the model and the analysis procedure are briefly discussed in this section. Multistoreyed building (with 5 bays in each direction, 5m c/c column spacing and 4m height of each storey) is modelled along with raft foundation. In dead load the self-weight of all the members is taken as per IS-875 Part-I, and the wall load of 20 kN/m as per IS 875 part-I is taken. Building is assumed to be institutional building and the live load of 4 kN/m^2 is considered as per IS-875 Part-II. Three different mesh sizes of plate element used to model foundation raft have been studied, viz., 0.25m, 0.5m and 1m mesh size to study the effect of mesh size on the foundation base pressure and settlement.

Different alternatives have been generated in STAAD Pro. by varying mesh size, intensity of loading (height of building), values of K_s and thickness of foundation as discussed above. Figs. 1, 2 and 3 shows the plan view, section view and 3-dimensional view of the building with raft foundation.

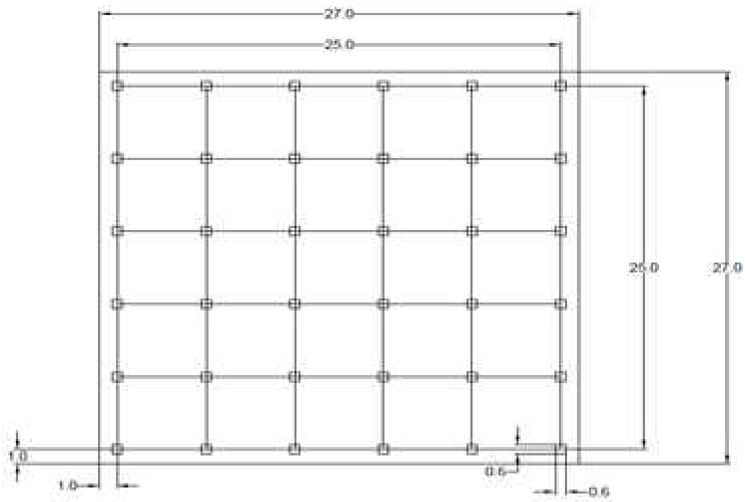
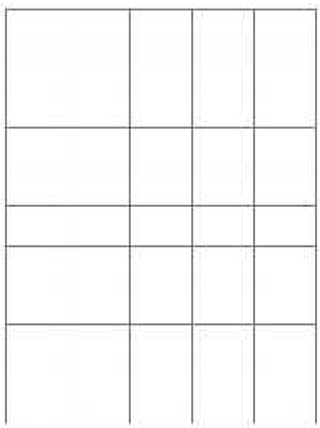


Fig. 1. Plan view of the building and foundation (All dimensions are in meters)



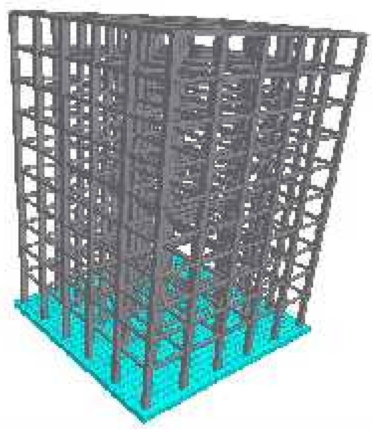


Fig. 2. Section view of model **Fig. 3**. 3-dimensional view of 10-storeyed building

2 Results from Finite Element Analysis of Foundation in STAAD Pro.

As per the discussed methodology the analysis of different models were performed in STAAD Pro. Total 12 alternatives were studied with varying mesh size, raft thickness, loading intensity and K_s values. The result obtained in terms of base pressure, total settlement and differential settlement are presented in graphical manner and discussed below.

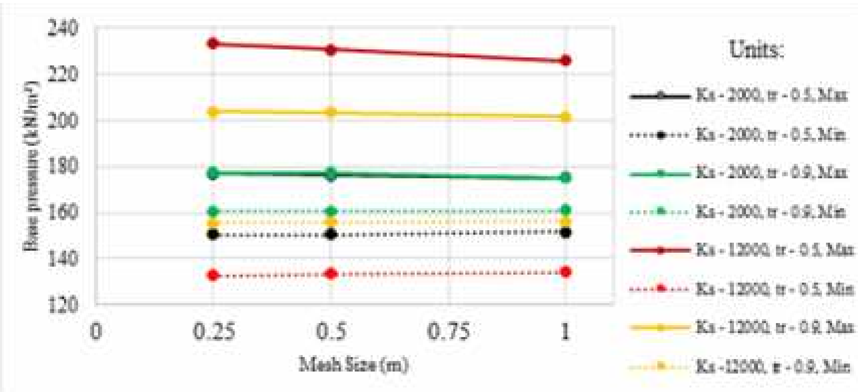


Fig. 4. Variation of Maximum and minimum base pressure with mesh size

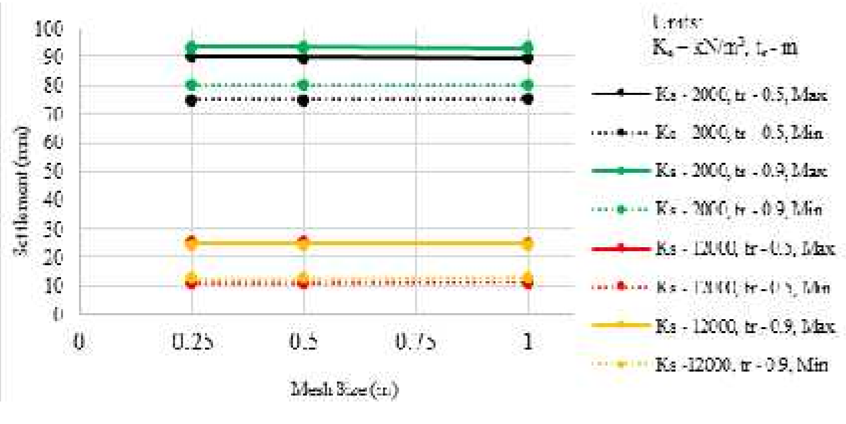


Fig. 5. Variation of settlement with mesh size

Figs. 4 and 5 present the maximum and minimum values of base pressure and settlement, respectively for different cases. Fig. 6 presents the variation of differential settlement for different cases. From Fig. 4 it can be observed that the variation in base pressure reduces with increase in mesh size. Further, it can be observed that difference in base pressure is relatively less for mesh size of 0.25m and 0.5m as compared to 0.5m and 1m. From Figs. 5 and 6, it can be observed that the total and differential settlement (difference between maximum and minimum settlement within raft foundation) is not affected much by mesh size. It is usually accepted fact that finer mesh size leads to more refinement of results. Hence, for all practical purposes, to achieve accurate results and reduce time of analysis for complex problems, it is recommended to use mesh size of 0.5m. From Fig.4 it can also be observed that for K_s = 12000 kN/m^3 and raft thickness of 0.5m, the variation in base pressure is maximum; whereas for K_s = 2000 kN/m^3 and raft thickness of 0.9m, the variation in base pressure is minimum. Further, from Figs. 5 and 6, it can be noted that as expected, the total and differential settlement is lower for higher values of K_s. The effect of K_s on base pressure and settlement variation is more prominent as compared to the effect of raft thickness.

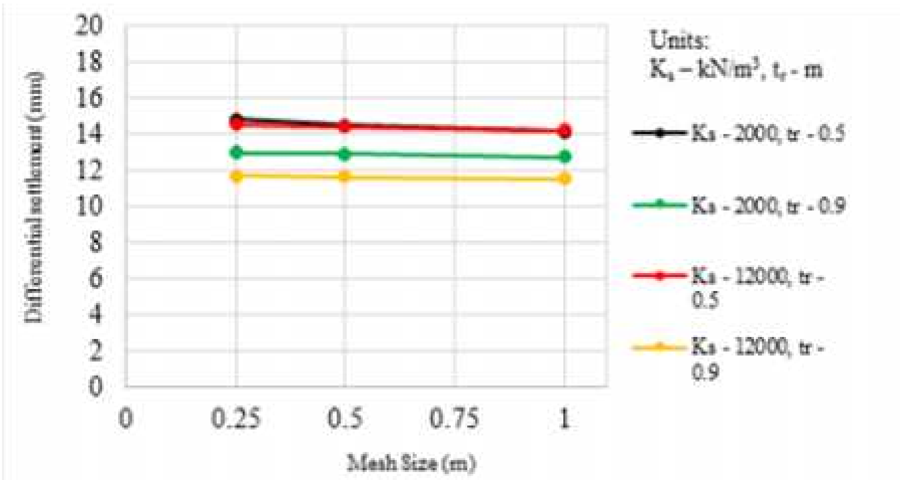


Fig. 6. Variation of differential settlement with mesh size

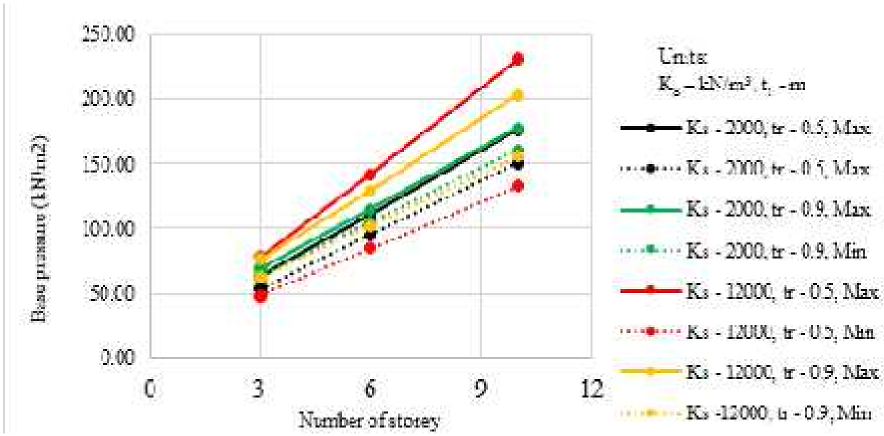


Fig. 7. Variation of base pressure with storey height for uniform distribution of K_s

Fig. 7 presents the maximum and minimum base pressure for different intensity of loading (viz., 3 storey building, 6 storey building and 10 storey building). It can be seen that base pressure increases linearly with increase in intensity of loading. The variation in maximum and minimum base pressure is highest for K_s = 12000 kN/m^3 and 0.5m foundation thickness and lowest for K_s = 2000 kN/m^3 and 0.9m foundation thickness. Hence foundation with higher thickness on relatively less stiff soil results in more uniform base pressure distribution. From Figs. 8 and 9 it can be inferred that settlement as well as differential settlement increases with increase in loading. Further, it can be inferred that the differential settlement for thicker foundation (0.9m) and stiffer soil (K_s = 12000 kN/m^3) is lowest as compared to other cases.

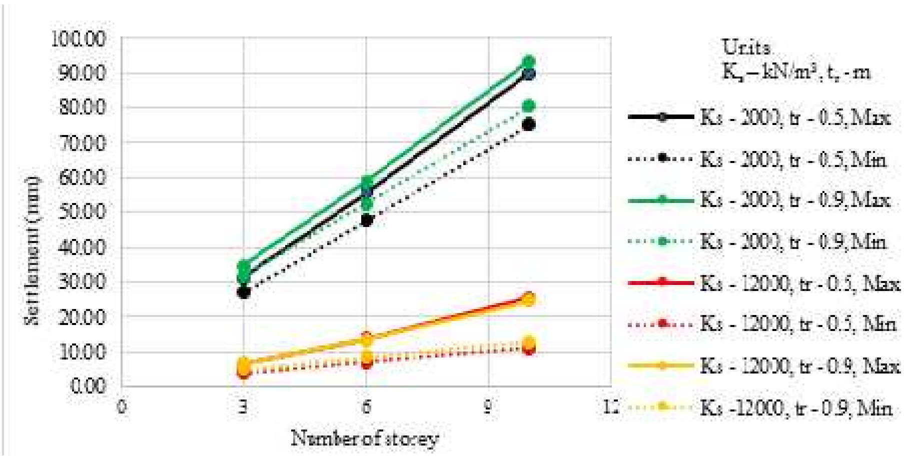


Fig. 8. Variation of settlement with storey height

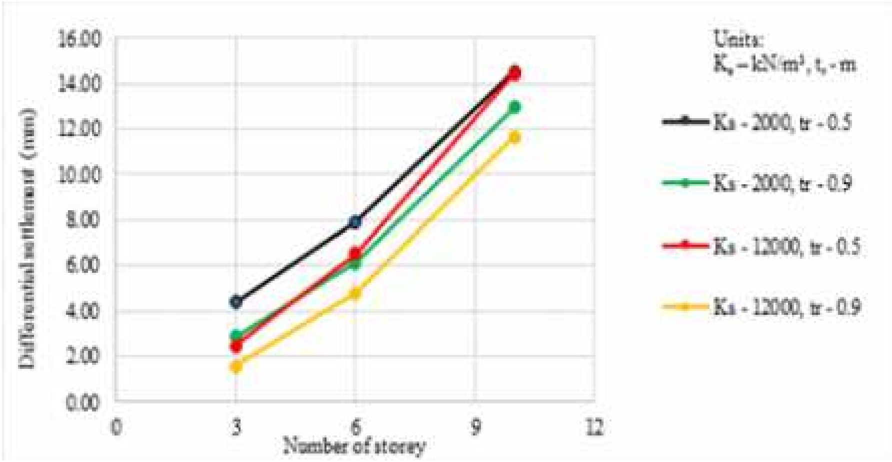


Fig. 9. Variation of differential settlement with storey height for uniform distribution of K_S

3 Conclusions

The present study evaluated the variation of base pressure, total as well as differential settlement for different foundation modeling mesh size, intensity of loading, K_s values and raft thickness. The following conclusions can be drawn from the study:

1. It can be observed from the study that the variation in base pressure and differential settlement within foundation reduces with increase in mesh size. Further, it can be observed that difference in base pressure is relatively less for mesh size of 0.25 m and 0.5 m. For all practical purposes, to achieve accurate results and reduce time of analysis, it is recommended to use mesh size of 0.5 m for STAAD Pro. analysis.
2. The base pressure variation for 0.5 m thick foundation on stiff soil (Ks = 12000 kN/m^3) is maximum (40-44% for different mesh sizes); whereas base pressure variation for 0.9 m thick foundation on soft soil (K_s = 12000 kN/m^3) is minimum (8-10% for different mesh sizes). Hence the relative stiffness of soil-foundation system has significant effect on base pressure variation within the foundation area.
3. The total and differential settlement (viz., difference between maximum and minimum settlement in mm) is minimum for higher values of K_s (12000 kN/m^3) and higher value of foundation thickness (0.9 m). The differential settlement is maximum for lower foundation thickness (for both K_s = 2000 kN/m^3 and K_s = 12000 kN/m^3). However, percentage of differential settlement (viz., percentage difference between maximum and minimum settlement) is observed to be higher for case with higher K_s (12000 kN/m^3) and lower foundation thickness (0.5 m). Similarly, percentage differential settlement is lower for Ks =2000 kN/m^3 (for foundation thick-

ness 0.5 m and 0.9 m). The effect of K_s on base pressure and settlement variation is more prominent as compared to the effect of raft thickness.

4. It can be concluded that base pressure increases with increase in loading. Further, settlement as well as differential settlement increases with increase in loading.

4 References

1. Aristorenas G. and Gomez J. 2014, Subgrade Modulus – Revisited. STRUCTURE magazine.
2. Barounis N., Orr T. L. L., McMahon P.H., Barounis A., 2009, Modulus of subgrade reaction for foundations on clay from unconfined compression tests, 17th International Conference on Soil Mechanics and Geotechnical Engineering.
3. Briaud J., L.June 2001, Introduction to Soil Moduli, Geotechnical News, BiTech Publishers Ltd, Richmond, B.C., Canada.
4. Dey A., Basudhar P.K., Chandra S., 2011, Distribution of Subgrade Modulus beneath Beams on Reinforced Elastic Foundations, Indian Geotechnical Journal, 41(2), 2011, 54-63.
5. Eimarakbi A. M., Budkowska B. B., 2001, Assessment of modulus of subgrade reaction of sand-sensitivity analysis,
6. Horvath J. S., 1983, Modulus of subgrade reaction: New perspective, ASCE, Geotech. Engg. 1983.109:1591-1596.
7. IS 875 Part I (1987): Code of Practice for Design Loads (Other than Earthquake) For Buildings and Structures. Part1: Dead Loads, Bureau of Indian Standards, New Delhi.
8. IS 875 Part II (1987): Code of Practice for Design Loads (Other than Earthquake) For Buildings and Structures. Part 2: Imposed Loads, Bureau of Indian Standards, New Delhi.
9. Larkela A., Mengelt M., Stapelfeldt T., Determination of distribution of modulus of subgrade reaction, International Conference on Soil Mechanics and Geotechnical Engineering, Paris 2013.
10. Teli, S., Kundhani, P., Choksi, V., Sinha, P. and Iyer, K. R. (2019), “Analytical Study on Influence of Rigidity of Foundation and Modulus of Subgrade Reaction on Behaviour of Raft Foundation”, International Symposium of International Association for Computer Methods and Advances in Geomechanics (IACMAG), March 2019, IIT Gandhinagar.
11. Terzaghi, K. 1955, Evaluation of coefficients of subgrade reaction. Geotechnique, Vol. 5, No. 4, 41-50.
12. Worku, A. 2009, Winkler's single-parameter subgrade model from the perspective of an improved approach of continuum-based subgrade modeling. Journal of EEA, Vol. 26.