# A preliminary approach on subway metro stations and their gravity signature

**Spyridon Dilalos [1] & John D. Alexopoulos [1]**

**Affiliation [1]**: National and Kapodistrian University of Athens, Department of Geology and Geoenvironment, Laboratory of Geophysics, Panepistiomioupoli Zografou, Greece

Dilalos Spyridon: sdilalos@geol.uoa.gr, https://orcid.org/0000-0002-6919-0223

Alexopoulos John D.: jalexopoulos@geol.uoa.gr, https://orcid.org/0000-0001-5197-8373

## Abstract

A specialized urban gravity survey was conducted using field measurements to determine the gravitational effects of human-made subsurface structures and, more specifically, subway stations. Large-scale underground infrastructure is common in urban environments and disturbs the gravity field. During such gravity surveys, data corrections for these types of disturbances should be calculated and applied to ensure accurate results. This study involves acquiring a set of time-lapse gravity measurements, at the location of a subway station, both before and after its construction. The gravity variation results from the removal of the subsurface geological material and its partial replacement with structural materials, as well as the void remaining and the covering of the station with loose materials. Beyond verifying the gravity anomaly caused by the metro station, the importance of the distance from the gravity station was also verified based on the field measurements, as expected. Based on the correlation between gravity variations and distance, the gravitational effect becomes negligible at approximately 95-100 meters. However, this finding requires validation through a larger dataset.

**Keywords**: urban geophysics, underground metro station, gravity measurements, Athens basin, gravity corrections.

## Resumen

Se llevó a cabo un estudio especial de gravedad urbana con el fin de determinar el efecto gravitacional de las estructuras subterráneas artificiales y, más concretamente, de las estaciones de metro, utilizando mediciones de campo. Las infraestructuras subterráneas a gran escala son habituales en las ciudades y perturban el campo gravitatorio. Durante un estudio de gravedad urbana, se deben calcular y aplicar correcciones de datos para este tipo de perturbaciones a fin de garantizar resultados precisos. Esto implica adquirir un conjunto de mediciones de gravedad a intervalos regulares, en la ubicación de una estación de metro, antes y después de su construcción. La variación de la gravedad se debe a la eliminación del material geológico subterráneo y su sustitución parcial por materiales estructurales, así como al vacío restante y la cubierta de la estación con materiales sueltos. Además de verificar la anomalía gravitacional causada por la estación de metro, también se ha verificado, como era de esperar, la importancia de la distancia desde la estación gravitatoria, basándose en las mediciones de campo. A partir de la correlación entre las variaciones gravitatorias y la distancia desde la estación de metro, el efecto de la gravedad se reduce a distancias de entre 95 y 100 metros aproximadamente, pero es necesario validarlo con un conjunto de datos más amplio.

**Palabras clave:** geofísica urbana, estación de metro subterránea, mediciones de gravedad, cuenca de Atenas, correcciones de gravedad.

## 1. Introduction

Athens is the capital city of Greece, with a population of 3.8 million people. The city's public transport system includes the metro network, which began operating in 2000, prior to the return of the Olympic Games to their country of origin. The subway system is fundamentally composed of two lines, the Red and the Blue, which are continuously being extended with the addition of new stations. More specifically, the Blue line has undergone significant expansion towards the Piraeus area in recent years, with the addition of six new subway stations, in the areas of *Agia Varvara, Nikaia, Maniatika, Korydallos, Dimotiko Theatro* (downtown *Piraeus*) and the Port of *Piraeus* (Figure 1) (Marinos *et al*., 2009; Schina & Charalampidou, 2014; Vogiatzis *et al*., 2018).

The authors have previously carried out extensive gravity mapping of the Athens region (Dilalos, 2018; Dilalos & Alexopoulos, 2017; 2019a; 2019b; 2020; Dilalos *et al*., 2018; 2019a; 2019b) in an effort to delineate the subsurface structure of such a highly urbanized area, given that other geophysical methods are often difficult to apply. In the context of this research, the authors calculated building corrections for each gravity station, in order to remove the building effect of the infrastructure. To further minimize such interference, gravity stations were primarily located in 'open' areas. During the acquisition period of these gravity measurements, between 2013-2015, the preparations for the construction of new subway stations as part of the so-called "*Piraeus extension*" of the Blue line, had already begun (Marinos *et al*., 2009; Schina & Charalampidou, 2014; Vogiatzis *et al*., 2018).

It is well known that removing subsurface material affects the gravity measurement of a nearby gravity station. In general, gravity and microgravity measurements have been applied in several urban areas primarily for detecting subsurface cavities (Bolaño *et al.,* 2005; Chromčák et al., 2016; Jacob *et al*., 2020; Piroddi *et al.*, 2021; Pueyo-Anchuela *et al.,* 2010; Thierry *et al.,* 2005; Tuckwell *et al*., 2008). Taking this into account, along with the construction of the new subway stations, the authors examine, through field measurements, how a metro station disturbs the local gravity field, in other words, the impact a subway station has on nearby gravity measurements.

It should be noted that the construction of a metro station not only involves the removal of underground geological material but also replaces part of the excavated area with construction materials, mainly concrete and steel, to support the structure. The rest of the excavated area is left vacant to accommodate train and passenger movement. Most of the stations were constructed using the cut-and-cover method (apart from *Maniatika*). Part of the excavation above the station's roof was inevitably backfilled with materials of lower density than the original geological formations. The interstation tunnels between were constructed using a tunnel-boring machine. The depths of these metro stations extend to 26-29 meters. The estimated affected subsurface volume ranges from 90,000-110,000 $m^3$.

In a few cases in the past, the gravity method has successfully contributed to subsurface investigations prior to or during the construction of subway metro stations and lines (Égető *et al*., 2014; Radogna *et al*., 2002; 2004; Su *et al*., 2021). On the other hand, buildings and infrastructure can affect nearby gravity measurements (Debeglia & Dupont, 2002;

Dilalos, 2018; Dilalos *et al*., 2018; Jacob *et al*., 2020; Loj & Porzucek, 2019; Nowell, 1999; Yu, 2014).

## 2. Geological and geotechnical setting

In Figure 1, we provide a simplified geological map of the greater area (Dilalos, 2018; Dilalos *et al*., 2019a) mostly based on the research by Papanikolaou *et al.* (2002). The geological regime across the Athens basin is quite complicated. However, not all geotectonic units of the basin appear at the investigated subway stations. Along the extension of the metro line, the Alpine basement of the allochthonous unit of "*Ypopelagoniki*" is overlain, in places, by the local allochthonous "*Athens Unit*".

The "*Ypopelagoniki*" unit is comprised mainly of Paleozoic clastic formations at its base and the overlying Triassic-Jurassic limestones. The "*Athens Unit*" is divided into two parts: the overlying limestones and the base part, known as "Athens Schists". The latter formation is a geological mélange including shales, schistic sand-gravel, breccia, meta-sandstones, phyllites, peridotites, limestones and marls.

Most of the region is covered by the Neogene and Quaternary deposits of the Athens basin. These include talus cones and scree (*Pt.sc*) or Pliocene terrestrial deposits (*Pll*) comprised of sand and clay along with Pliocene marine deposits (*Plm*) in the Piraeus peninsula, with sandstones, marls, breccioconglomerates, marly limestones with sandstone intercalations and limestones.

Data from 125 sampling boreholes executed during the preparatory phase of the subway construction (Marinos *et al.,* 2009) revealed that *Agia Varvara* station is located on terrestrial marly deposits, while *Korydallos* and *Nikaia* stations are located on Athens

Schists, covered by talus cones and scree. Furthermore, *Maniatika* station has been built on ophiolites and limestones whereas *Dimotiko Theatro* station was constructed in marine marly limestones.

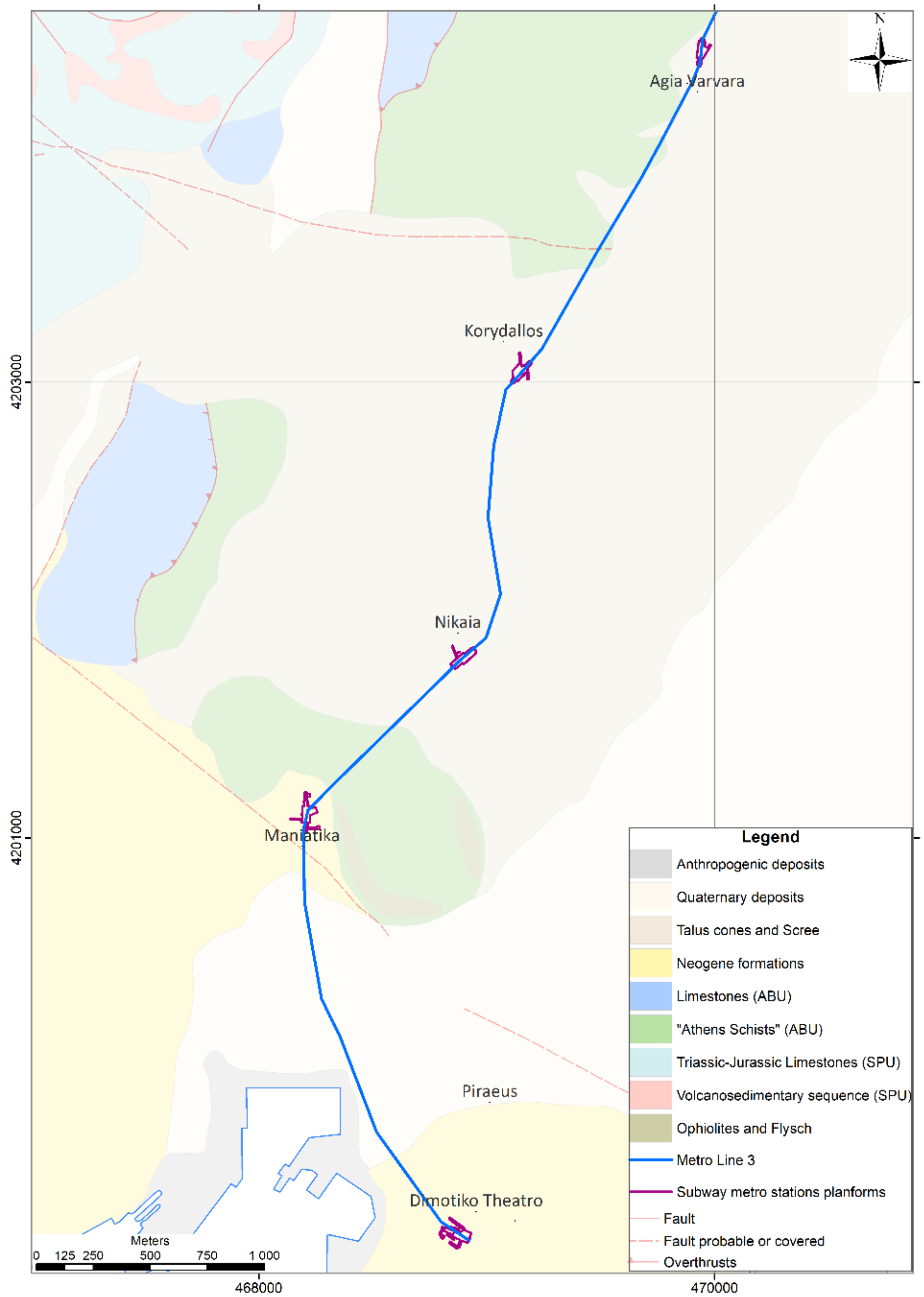


**Figure 1.** Simplified geological map of the area along the extension of Athens metro line 3 (blue line). The purple lines delineate the investigated metro stations planforms.

## 3. Gravity survey

### 3.1 Data acquisition

The initial gravity measurements in the areas of interest were acquired during the summer of 2013. Repeated measurements at the *Nikaia, Agia Varvara* and *Korydallos* stations were acquired during the summer of 2020, whereas those of the *Maniatika* and *Dimotiko Theatro* stations were acquired during the summer of 2023 due to their delayed completion.

All sets of measurements, both prior to and after construction, were acquired at the same location, each with multiple readings for verification. The locations were determined via Differential Global Positioning System (dGPS). Two individual, dual-frequency GPS antennas, were utilized, providing a vertical precision ranging from 0.6 to maximum 2.4 cm. The coordinates were determined using the Hellenic Geodetic Reference System (GGRS'87). To ensure consistency, all gravity measurements were acquired by the same person, employing the same instrument, Lacoste-Romberg G-496. Good measurement reproducibility over the years, was verified by revisiting other gravity stations around the subway stations, where no differences were expected. The *Dilaveri* gravity base, which was used for the necessary drift corrections and comparisons, is referenced to the IGSN'71 datum (Morelli *et al*., 1974). It was established by the authors in previous works (Dilalos, 2018; Dilalos & Alexopoulos, 2019a). Furthermore, extensive photographic documentation of the surrounding area and buildings was conducted during each measurement. This allowed for the identification of any potential alterations that should be considered. Potential alterations of the gravity field included new buildings, apart from those connected to the subway station. Based on these data, no infrastructure changes were observed at the closer area of the gravity station, other than the ones directly related to the subway station.

Selecting the exact location for each gravity station proved to be challenging, as it had to meet certain criteria. For example, the elevation of the gravity station should not alter after the station's completion (e.g., due to infrastructure construction at the specific location, such as walls or decorative platforms). Additionally, we had to avoid future artificial voids at the location of the measurement, such as ventilation shafts, station exits, stairs or escalators. The location needed to be relatively quiet, situated away from traffic or operating escalators, to avoid intense oscillations of the instrument during measurements. Finally, the location of the gravity station had to remain accessible for measurements, both prior to and after the construction phase. During the initial measurements, security fences were placed around the areas that would be excavated. At this stage, the published ground plans of the subway station ("*Line 3 Extension Chaidari-Piraeus Stations"*) were immensely helpful. By consulting these plans, we could identify where planned structures that should be avoided, such as stairs, escalators, elevators, ventilation upcasts, fountains, trees and new streets. This allowed us to identify areas of significant altitude change due to artificial structures.

Moreover, the gravity measurement should preferably be acquired as close as possible to the main area lacking mass, which is practically the estimated center of the underground station. In theory, the gravity difference will be greater the closer we get to the main excavated underground volume that remains empty. Unfortunately, in some stations, such as *Agia Varvara*, safety-related accessibility restrictions prevented the gravity measurement from being taken as close to the station planform.


**Figure 2.** The stations planforms (red lines), based on the official ground plans along with the location of the gravity stations (red dots).

Taking into account all these criteria and considerations, the gravity stations were placed as illustrated in Figure 2, where the stations planforms have also been plotted, based on the georeferenced official ground plans in ArcGIS Pro.

### 3.2 Gravity Values

We applied only the drift and tide corrections to calculate the absolute values of each pair of gravity measurements (prior to and after construction) using Oasis Montaj software. Given that there were no changes in the terrain elevation of the closer area around the gravity stations, we did not apply terrain corrections or the Bouguer anomaly. As noted in the previous section, the gravity stations were strategically positioned to ensure that terrain corrections remain negligible. Specifically, no significant alterations were observed within the inner 20-meter segment. On the broader section of 50 meters, minor variations in structural characteristics were estimated to be less than 0.01 mGal.

The drift corrections were performed by reoccupying the *Dilaveri* reference base every couple of hours. The whole process was completed within a day to minimize the effect. Tide corrections are typically calculated with an error of ±0.005 mGal, while the raw reading error for the specific instruments is no greater than 0.01 mGal (Dilalos & Alexopoulos, 2020). Therefore, the total estimated error is no more than 0.010-0.015 mGal. This uncertainty in small relative to most observed differences (Table 1). However, the *Agia Varvara* value is below the estimated uncertainty of the survey.

Table 1 presents the absolute gravity values of the initial and repeat measurements of all investigated locations/stations (prior to and after construction). The fourth column illustrates the gravity difference between the two measurements of each set. This reveals that the gravity field at the gravity station varied due to the construction of the corresponding metro station. As expected, the differences are negative, indicating a decrease in gravity values after the completion of the underground station.

The average density of the subsurface volume at each station has been reduced for two reasons. Originally, the main artificial void was created due to the extended removal of (geological) mass during the construction excavations, which were partially filled in with the reinforced concrete of the station. Secondly, the constructed stations were backfilled up the original ground surface level with materials of lower density than the pre-existing geological formations.

| Subway station | Initial absolute gravity value (mGal) | Repeat absolute gravity value (mGal) | Gravity difference (mGal) | Distance from station's center (m) |
|---|---|---|---|---|
| *Agia Varvara* | 980042.978 | 980042.977 | - 0.001 | 95 |
| *Nikaia* | 980049.672 | 980049.366 | - 0.306 | 28 |
| *Korydallos* | 980044.687 | 980044.569 | - 0.118 | 70 |
| *Maniatika* | 980050.183 | 980049.943 | - 0.240 | 55 |
| *Dimotiko Theatro* | 980047.492 | 980047.107 | - 0.384 | 20 |

**Table 1:** The sets of gravity values, before and after the stations' construction, their gravity variation along with their estimated horizontal distance from the stations' center.

## 4. Discussion

The reduction in gravitational attraction of the surface buildings is well documented (Debeglia & Dupont, 2002; Dilalos *et al.*, 2018; Loj & Porzucek, 2019; Yu, 2014), establishing that gravitational attraction weakens as the distance from a building increases. It is also known that the force of gravity decreases with the inverse square of the distance. Based on this principle, we examined the corresponding correlation of our observations, derived from the gravity field measurements prior to and after the construction of the subway stations.

The variation in gravity resulting from the construction of a subway station is also affected by the type (and density) of the geological formation in which it is built. Usually, most subway stations are built in post-Alpine formations, with relatively low densities. As previously mentioned, the *Agia Varvara* and *Dimotiko Theatro* stations are clearly located in post-alpine deposits, with calculated densities of 1.96 and 2.5 gr/cm$^3$ respectively (Dilalos, 2018; Dilalos *et al.,* 2019a). *Korydallos* and *Nikaia* are built in the Athens Schists mélange, with a density of 2.50 gr/cm$^3$, and the *Maniatika* station is built in alpine formations (2.67 gr/cm$^3$). This could explain the greater reduction in gravity values at the latter station, given the greater density difference. We can adopt a density of 0.44 gr/cm$^3$ for the subway station structure, based on the building's density, previously calculated by the authors (Dilalos *et al.,* 2018). Therefore, the density difference per station would be 1.52 gr/cm$^3$ for *Agia Varvara*, 2.06 gr/cm$^3$ for *Dimotiko Theatro, Korydallos and Nikaia* and 2.23 gr/cm$^3$ for *Maniatika* station.

Several additional factors, such as the depth of the station, the volume of subsurface excavation and the construction method, also influence gravity variations. As already discussed in the introduction section, there are no significant differences among the stations regarding these parameters.

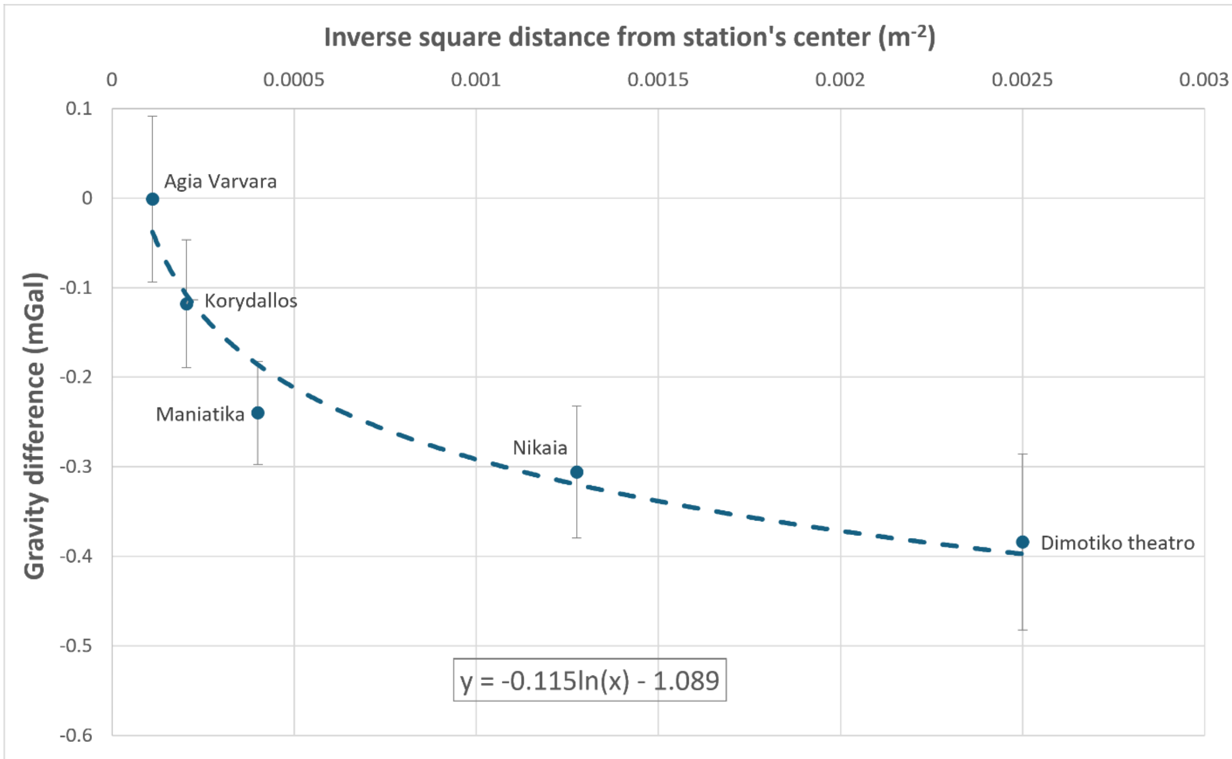


**Figure 3.** The correlation between the inverse square distance of the gravity measurement from the estimated center of the station with the determined gravity variation before and after its construction.

Considering the aforementioned factors, Figure 3 illustrates the correlation between the inverse square distance ($1/r^2$) of the gravity measurement from the estimated center of the metro station and the corresponding calculated gravity variation detected after the station's completion. A logarithmic trendline has been drawn to examine the fit of the plotted data leading to the following fitting equation:

$$y = -0.115ln(x) - 1.089 \quad (1)$$

where y stands for the gravity variation/difference in mGal and x represents the inverse square distance ($1/r^2$) in $m^{-2}$ at which the gravity measurement was acquired from the center of the underground metro station in meters.

According to the statistical analysis of the data, the fit explains 94.9% of the variance ($R^2$=0.949). Given that only five stations contribute to the regression, the residual degrees of freedom are three, thereby forcing the t-critical value to 3.18. The logarithmic relationship proposed should be handled with caution, given the constraints of the limited dataset. Although the fit is statistically significant (p=0.005), the limitations imposed by the small sample size preclude the possibility of robust generalization. Consequently, the fitted equation should be regarded as a first-order empirical observation rather than a validated predictive model. The 95% confidence interval (CI) for the slope is entirely negative, ranging from −0.165 to −0.066. Three stations fall within ±0.014 mGal of the fitted line, which is excellent relative to the RMSE of 0.040 mGal. The gravity difference recorded at *Agia Varvara* (−0.001 mGal) falls within the total measurement uncertainty of ±0.010–0.015 mGal and cannot therefore be treated as a resolved gravity anomaly. *Maniatika* station is the outlier with a residual of -0.054 mGal, a value that is noticeably below the log fitting curve (Figure 3), probably because it is located in relatively denser geological formations (limestones and ophiolites). The residual could also be affected by the geometry. The error bars of Figure 3 provide a fit-confidence uncertainty only.

Based on these data, it seems that an almost negligible gravity difference will be detected at a distance of ninety-five meters from a subway station. For the stations analyzed, the results suggest that the gravity effect caused by a subway metro station becomes small at distances close to 95-100 m. Therefore, in similar urban settings, this distance may be used as a preliminary first-order indication.

It must be emphasized that there is only data from five sets of gravity measurements, one for each metro station. This does not allow us to examine the spatial distribution of the gravity variations close to the metro stations but only provides indications of it. The sample is small to make robust inferences and the results should be considered preliminary.

Finally, as a first-order verification, a simplified point-mass forward model was applied. The aforementioned representative density contrasts and distances of each station have been used along with a mean depth of 27 m and an approximate box volume of 60,000 $m^3$. The model predicts gravity differences of 0.587, 0.378, 0.105, 0.053 and 0.017 mGal at distances of 20, 28, 55, 70 and 95 m respectively. These estimates are consistent with the observed values (Table 1) in terms of both order of magnitude and rate of reduction, supporting the physical interpretability of the results. Discrepancies are attributed to station-specific geometry, geological variability, and the simplifications inherent in a point-mass approximation.

## 5. Conclusions

The impact of human-made infrastructure on gravity variation remains a relatively understudied field. The necessity of urban geophysical studies is becoming increasingly evident from several perspectives. Therefore, future urban gravity studies must fully understand the effect of surface and subsurface infrastructures on gravity data acquisition in order to remove them if necessary. Building corrections have already been studied over the last decade, as we have already mentioned, using either forward modelling or the results of field surveys. In this paper, we demonstrate the gravity effect of large-scale subsurface structures, such as the subway stations, based on field gravity measurements.

Not only have we determined the gravity disturbance of the metro stations but we have also confirmed once again that distance from the center of the gravity anomaly (here the subway station) is a crucial factor. The data suggests that, for the stations analyzed, the gravity effect becomes negligible at distances of approximately 95-100 meters. However, this estimate requires validation using a larger dataset. A similar approach and correction could be readily adopted to other large-scale subsurface infrastructure, such as underground car parks. The proposed distance of 100 meters aligns closely with existing literature (Dilalos, 2018; Dilalos *et al.,* 2018; Debeglia & Dupont, 2002; Nowell, 1999) regarding the minimization of the gravitational attraction of buildings or basements.

Ultimately, further study is required into the spatial distribution of gravity variation resulting from such constructions. To address this, the authors have initiated a similar investigation at other metro stations under construction (Line 4), by acquiring several gravity measurements around the stations. To better understand the spatial distribution of the expected gravity differences, time-lapse gravity measurements have been planned on a grid covering the area of the future metro station. Once these stations are completed, repeat gravity measurements will be acquired to provide a more robust understanding.

## 6. Acknowledgments

The authors would also like to express gratitude to Ms. Achtypi S. and Mr. Petroulias for their significant contribution to field acquisition.

## 7. References

Bolaño, V., Calvo, C., Martín, A. M., Carbó, A., 2005. Geophysical Study for the Detection of Voids and Low Density Anomalies in Urban Areas. In: *67th EAGE Conference and Exhibition, cp-1*. European Association of Geoscientists & Engineers.

Chromčák, J., Grinč, M., Pánisová, J., Vajda, P., Kubová, A., 2016. Validation of sensitivity and reliability of GPR and microgravity detection of underground cavities in complex urban settings: Test case of a cellar. *Contributions to Geophysics and Geodesy*, 46 (1), 13-32. https://doi.org/10.1515/congeo-2016-0002

Debeglia, N. & Dupont, F., 2002. Some critical factors for engineering and environmental microgravity investigations. *Journal of Applied Geophysics*, 50 (4), 435-454. https://doi.org/10.1016/S0926-9851(02)00194-5

Dilalos S., 2018. Application of geophysical technique to the investigation of tectonic structures in urban and suburban environments. A case study in Athens basin. *Ph.D. Thesis* National and Kapodistrian University of Athens. http://hdl.handle.net/10442/hedi/48791

Dilalos S., Alexopoulos J.D., 2017. Indications of correlation between gravity measurements and isoseismal maps. A case study of Athens basin (Greece). *Journal of Applied Geophysics,* 140, 62-74. https://doi.org/10.1016/j.jappgeo.2017.03.012

Dilalos S., Alexopoulos J.D., Tsatsaris A., 2018. Calculation of Building Correction for urban gravity surveys. A case study of Athens metropolis (Greece). *Journal of Applied Geophysics* 159 (C), 540-552. https://doi.org/10.1016/j.jappgeo.2018.09.036

Dilalos S., Alexopoulos J.D., 2019a. Urban Gravity Measurements for the Subsurface Investigation of Athens Basin (Greece). *Bulletin of the Geological Society of Greece* Special Publication 7, 211-212.

Dilalos S., Alexopoulos J.D., 2019b. Quantitative subsurface information of Athens basin (Greece) derived from urban gravity measurements. In: *Near Surface Geoscience 2019 - 1st Conference on Geophysics for Infrastructure Planning Monitoring and BIM,* We_INFRA_P23. https://doi.org/10.3997/2214-4609.201902560

Dilalos S., Alexopoulos J.D., Lozios S., 2019a. New insights on Athens basin (Greece) subsurface geological and tectonic structure, derived from urban gravity measurements. *Journal of Applied Geophysics* 167 (C), 73-105. https://doi.org/10.1016/j.jappgeo.2019.04.024

Dilalos S., Alexopoulos J.D., Lozios S., 2019b. The contribution of urban gravity survey to the subsurface geological structure of the Athens basin (Greece). In: *Near Surface Geoscience 2019 - 25th European Meeting of Environmental and Engineering Geophysics*, We_25_P17. https://doi.org/10.3997/2214-4609.201902472

Égető, C., Rehány, N., & Földváry, L., 2014. Variations of the gravity field due to excavations of the Budapest Metro4 subway line. *Periodica Polytechnica Civil Engineering*, 58 (2), 131-136. https://doi.org/10.3311/PPci.7489

Jacob, T., Pannet, P., Beaubois, F., Baltassat, J. M., Hannion, Y., 2020. Cavity detection using microgravity in a highly urbanized setting: A case study from Reims, France. *Journal of Applied Geophysics*, 179, 104113. https://doi.org/10.1016/j.jappgeo.2020.104113

Line 3 Extension Chaidari-Piraeus Stations. https://www.emetro.gr/?page_id=15352 (*accessed on 14th September 2024*)

Loj, M. & Porzucek, S., 2019. Detailed analysis of the gravitational effects caused by the buildings in microgravity survey. *Acta Geophysica*, 67 (6), 1799-1807. https://doi.org/10.1007/s11600-019-00336-9

Marinos, P. G., Novack, M., Benissi, M., Stoumpos, G., Papouli, D., Panteliadou, M., Marinos V., Boronkay K., Korkaris, K., 2009. Assessment of ground conditions with respect to mechanised tunnelling for the construction of the extension of the Athens Metro to the city of Piraeus. *Bulletin of engineering geology and the environment*, 68, 17-26. https://doi.org/10.1007/s10064-008-0183-9

Morelli C., Gantar C., Honkasalon T., McConnel K., Tanner J.G., Szabo B., Uotila U., Whalen C.T., 1974. *The International Standardization Net 1971 (IGSN71)*. IUGG-IAG Publication Special 4, International Union of Geodesy and Geophysics.

Papanikolaou D., Lozios S., Sideris C., Kranis H., Danamos G., Soukis K., Skourtsos E., Bassi E., Marinos P., Tsiampaos G., Boukovalas G., Sabatakakis N., Antoniou A., Provia K., 2002. Geological-Geotechnical study of Athens basin. *OASP Applied research program*, Athens (*In Greek*).

Nowell, D.A.G., 1999. Gravity terrain corrections—an overview. *Journal of Applied Geophysics*, 42(2), 117-134. https://doi.org/10.1016/S0926-9851(99)00028-2

Piroddi, L., Calcina, S. V., Erriu, S., Trogu, A., Ranieri, G., 2021. Integrated active and passive geophysical methods to explore underground soils in urban scenarios: the case of Stampace alto in Cagliari (Italy). In: *2<sup>1st</sup> International Conference on Computational Science and Its Applications (ICCSA)*, 234-241. IEEE.

Pueyo-Anchuela, O., Casas-Sainz, A.M., Soriano, M.A., Juan, A.P., Ipas-Lloréns, J.F., Ansón-López, D., 2010. Integrated geophysical and building damages study of karst effects in the urban area of Alcalá de Ebro, Spain. *Zeitschrift für Geomorphologie*. Supplementband, 54 (2), 221.

Radogna, P.V., Olivier, R., Logean, P., 2002. An underground railway project in Lausanne, Switzerland, as urban micro-gravity test site. In: *8th EEGS-ES Meeting*, cp-36. EAGE. https://doi.org/10.3997/2214-4609.201406213

Radogna, P.V., Olivier, R., Logean, P., 2004. A Subway Project In Lausanne, Switzerland, As An Urban Microgravimetry Test Site: Acquisition, Correction Of Buildings Influence And Modeling. In: *17th EEGS Symposium on the Application of Geophysics to Engineering and Environmental Problems*, cp-186. EAGE.

Schina, S. & Charalampidou, A., 2014. Athens metro line 3: complex tunnel geometries. *Geotechnical and Geological Engineering*, 32 (6), 1451-1466. https://doi.org/10.1007/s10706-013-9706-7

Su, M., Zhao, Y., Xue, Y., Wang, P., Xia, T., Zhang, K., Li, C., 2021. Progressive fine integrated geophysical method for karst detection during subway construction. *Pure and Applied Geophysics*, 178, 91-106. https://doi.org/10.1007/s00024-020-02636-4

Thierry, P., Debeblia, N., Bitri, A., 2005. Geophysical and geological characterisation of karst hazards in urban environments: application to Orléans (France). *Bulletin of Engineering Geology and the Environment*, 64, 139-150. https://doi.org/10.1007/s10064-004-0247-4

Tuckwell, G., Grossey, T., Owen, S., Stearns, P., 2008. The use of microgravity to detect small distributed voids and low-density ground. *Quarterly Journal of Engineering Geology and Hydrogeology*, 41 (3), 371-380. https://doi.org/10.1144/1470-9236/07-224

Vogiatzis, K., Zafiropoulou, V., Mouzakis, H., 2018. Monitoring and assessing the effects from Metro networks construction on the urban acoustic environment: The Athens Metro Line 3 Extension. *Science of the total environment*, 639, 1360-1380. https://doi.org/10.1016/j.scitotenv.2018.05.143

Yu, D., 2014. The influence of buildings on urban gravity surveys. *Journal of Environmental and Engineering Geophysics*, 19 (3), 157-164. https://doi.org/10.2113/JEEG19.3.157