Experiences on geophysical inspection of retaining wall structures

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ABSTRACT: Retaining walls make up an integral part of the infrastructure, therefore there is a strong interest in the assessment of their structural health and integrity. Although visual inspection can provide some hints about the actual state of these structures, the information obtained this way necessarily stays limited. To gain a better understanding, we can rely on geophysics too, using its various methods. Different geophysical measurements can be used not only to gather information about the geometry and the structural health of the retaining walls themselves but also about their backfills and the underlying structures. We present examples for three of the most common engineering geophysical methods used in our practice: GPR, seismic, and DC electric surveys. Since there are multiple types of retaining walls, some geophysical methods are better suited to investigate a certain type than others. Therefore, we also point out the difference in the geophysical approach in the cases of gravity retaining walls and gabion walls: while gravity retaining walls can be investigated themselves with either GPR or seismic methods, in the case of gabion walls we focus rather on the backfill and the underlying structures, using seismic and DC electric methods. To go even further, we also consider the relationship between physical parameters obtained with geophysical methods and some geotechnical parameters, which may be more directly related to the actual structural strength of a given structure. Namely, we calculate shear modulus (G_0) and pseudo-SPT(N) values from seismic velocities, using empirical relationships.

Keywords: retaining wall; gabion wall; geophysics; structural strength; structural integrity

1. Introduction

Retaining walls have a widespread usage as integral parts of road and railway infrastructures, where a large amount of soil has to be retained due to a steep slope. There exist many different types of retaining walls, here, we present some examples for two types: 1) gravity retaining walls, which are often built from stones, bricks, or concrete, and they depend on their mass to resist pressure from the backfill; and 2) gabion-mesh-strengthened walls, which consist of a wire cage filled with roughly cut stone or similar material to support the soil behind it. While gravity retaining walls need careful management of (rain) water, gabion walls are free-draining by nature. Therefore the latter is often the preferred type of choice in locations where significant water can be found on the surface or close to that (e.g., areas with shallow groundwater table).

As a geophysical service provider, MinGeo Ltd. is often commissioned with the inspection of critical infrastructure, including retaining walls. Probably the easiest and most common technique to investigate a retaining wall is to perform a visual inspection and take note of any suspicious mark and sign of degradation/corrosion, etc. A somewhat more sophisticated inspection of weep holes and vents can be carried out with a camera. This way the current state of the weep holes and vents can be verified. For example, we can tell whether a hole is still functioning to drain water from the backfill, whether a hole is clogged by soil/gravel/vegetation, or whether a weep hole pipe is broken. However, these methods cannot investigate the entire internal part of a retaining wall, nor they are capable to provide information about the backfill in every case.

As opposed to regular visual inspection, there are various geophysical methods to inspect retaining walls. These methods enable us to see beyond the face of a retaining wall and gather information about its internal structure and/or its backfill, as well as about its integrity and structural strength. Depending on the type of the wall, its location (e.g., next to a road or in the middle of a forest), dimensions, and accessibility, we have a wide range of geophysical methods to choose from. Here, we present examples for the three most common methods that we use to investigate retaining walls, namely, ground-penetrating radar, seismic, and electric methods. The paper is also organized around these three methods, and each method is presented through some real-life case studies, which were carried out as part of our geophysical service in the last few years.

2. Ground-penetrating radar (GPR)

GPR uses high-frequency radio waves (typical frequency between 10-3000 MHz) to map subsurface heterogeneities related to changes in dielectric properties (e.g., relative permittivity, conductivity). The principle of GPR measurements is that the GPR antenna emits a radio wave, which then propagates inside the wall. Upon the propagation, the electromagnetic wave may be reflected, diffracted, or transmitted, depending on the electromagnetic properties of the wall. In general, high conductivity materials, such as wet sand/concrete or clay attenuate significantly the radar waves. On the contrary, GPR can reach great penetration depths, for example, in dry concrete. Eq. (1) shows that the reflectivity R of a GPR wave depends on the dielectric contrast between the adjacent materials, where ε_1 and ε_2 are the relative permittivity of the two materials, respectively.

$$R = \frac{\sqrt{\varepsilon_2}-\sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2}+\sqrt{\varepsilon_1}} \quad (1)$$

Table 1. shows the dielectric constant at 1 GHz of some materials typically encountered in a retaining wall [1]. Since the dielectric constant of the different materials varies between 1 and 81, GPR is well-suited to investigate retaining walls and their structural changes.

Table 1. Dielectric constant (ε_r) of different materials at 1 GHz after [1]

Material	**Dielectric constant**
Air	1
Dry masonry	3-5
Moist masonry	5-26
Dry concrete	5-8
Moist concrete	8-16
Basalt	8
Dry clay/sands	4-8
Wet clay/sands	16-32
Water	81

2.1. Field examples

As opposed to visual inspection, GPR enables us to see beyond the face of a retaining wall and gather information about its internal structure and integrity too. As part of GPR inspection, we can determine the thickness of a gravity retaining wall and its change in both vertical and horizontal directions. In the case of reinforced concrete walls, the position, structure, and integrity of the reinforcement can also be investigated with GPR. Furthermore, should there be any crack/void filled with water/air instead of the original material/mortar, GPR can detect and characterize them. For example, Fig. 1. shows a case study for the GPR inspection of a gravity retaining wall in Budapest. The wall was built from blocks of quarry stone, and the goal of the inspection was to identify any void inside the wall or behind that. During the measurements, the wall was scanned along horizontal lines with a GSSI 900 MHz instrument. Fig. 1. (b) shows a rather intact section, where the rear face of the wall can be easily interpreted together with the joints among the building blocks. Some cracks can also be identified, mainly towards increasing block numbers. Although these cracks can seriously compromise the structural integrity of the retaining wall, they could not be detected by visual inspection as they are located behind the front face. Rather, GPR surveying is needed to map and characterize them. Fig. 1. (c) shows another section of the same wall, where significant voids are detected by the GPR both inside the wall and behind that in the backfill. Again, these voids – which had to be injected later by technicians –, would not have been detectable by visual inspection from the front face.

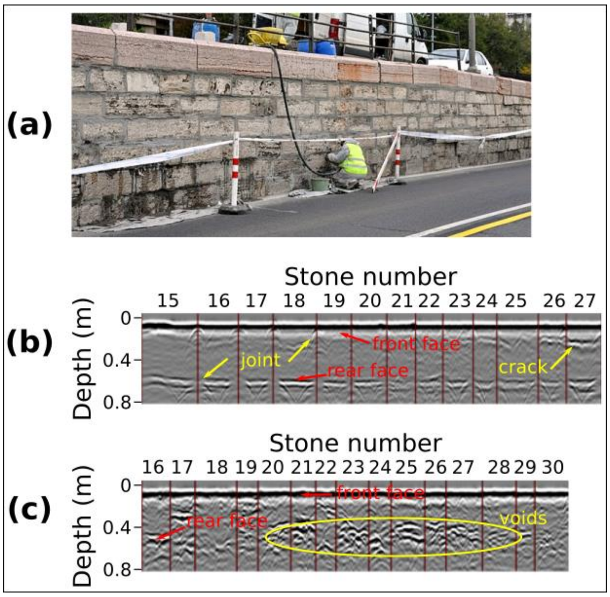

Figure 1. Examples for the GPR inspection of a gravity retaining wall in Budapest: (a) front face of the inspected stone masonry wall, (b) GPR image of a rather intact section with only a few cracks, but with no voids; (c) GPR image of another section with significant voids inside the wall and in the backfill as well.

Fig. 2. shows an example of a masonry gravity retaining wall. The wall was built at the beginning of the 20th century to retain soil next to a steeply-inclined hillside in Hungary. Some patches of different colors could be seen on the front face of the wall, and it was necessary to make sure the wall had still the necessary structural integrity, including the identification of any zones with potential voids or accumulated water. Two visible patches are annotated in Fig. 2. (a), while the corresponding GPR section is shown in Fig. 2. (b). The latter shows that the thickness of the retaining wall changes between 55-90 cm along the section, and there are also two significant voids in the backfill, exactly behind the two annotated patches visible on the front face. In this case, the corresponding weep holes below the patches proved to be clogged, therefore a significant amount of water could accumulate behind the wall. As the weep hole was not functional for a long time, the accumulated water started to seep through the masonry wall, resulting in visible patches.

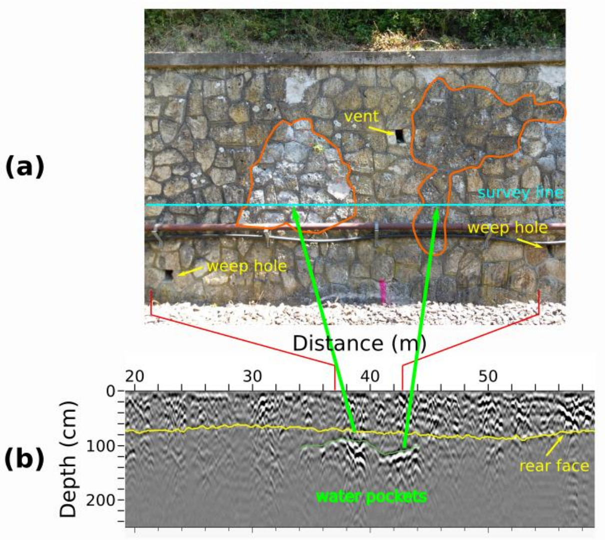

Figure 2. Example of a gravity retaining wall: (a) front face of the inspected wall with two annotated visible patches (orange polygons); (b) corresponding GPR section where voids originating in the backfill can be detected behind the visible patches.

3. Seismic method

According to Hooke's law, the propagation velocity of compressional P- (V_P) and S-waves (V_S) and the maximum value of the dynamic shear modulus (G_0) can be expressed mathematically with the help of the two Lamé-constants and density:

$$V_P = \sqrt{\frac{\lambda+2\mu}{\rho}} \quad (2)$$

for P-waves,

$$V_S = \sqrt{\frac{\mu}{\rho}} \quad (3)$$

for S-waves, and

$$G_0 = \rho \cdot V_s^2 \ (4)$$

where ρ, λ, and μ denote the density, the first Lamé parameter, and the second Lamé parameter, respectively. Since the propagation of seismic waves is related to the mechanical properties (e.g., density, porosity, fluid content) of the subsurface, seismic methods can be used to characterize the retaining walls and their backfills too.

During a seismic survey, mechanical waves are used to map heterogeneities related to changes in the mechanical properties of the subsurface. The seismic waves are generated on the surface and propagate into the subsurface. The field survey consists of the recording of the different waves arriving at the array of receivers. In the case of seismic tomography, the data recorded on the field is then used to solve an inverse problem to construct a model of the subsurface. The output of the inversion is usually a velocity map of the subsurface, but as we have seen above, with the help of deterministic relations, other attributes can be also calculated.

3.1. Field examples for gravity retaining walls

Additionally to the GPR method, gravity retaining walls can also be investigated with seismic methods. Of course, it would be optimal to carry out both P- and S-wave seismic measurements on these walls, but in practice, it is extremely difficult to generate S-waves on them, therefore we mostly rely on P-waves only. Seismic tomography can be used to characterize the strength of gravity retaining walls. The layout of a typical seismic tomographic field survey is shown in Fig. 3. Receivers are deployed on top of the wall and seismic waves are generated with a sledgehammer close to the bottom of the front face. The waves propagate through the wall, then reach the receivers on the top, where they are recorded in time.

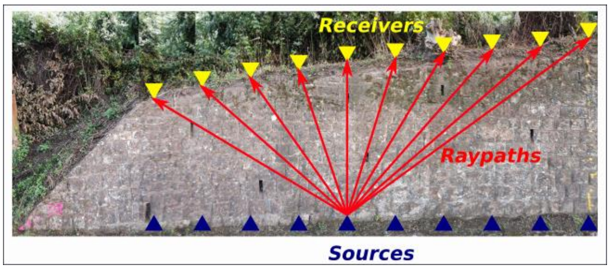

Figure 3. Typical seismic tomography survey layout for a gravity retaining wall. Seismic waves are generated close to the bottom of the front face (blue triangles), while the receivers are deployed on top of the wall (yellow triangles). The red lines show the hypothetical raypaths from a given source to the receivers if the wall was homogeneous.

Fig. 4. shows an example of a masonry gravity retaining wall. The wall was built at the beginning of the 20th century to retain soil next to a steeply-inclined hillside in Hungary. The wall had been visually inspected before the geophysical survey. The visual inspection is presented in Fig. 4. (a), showing some renovated areas, areas with seeping-water patches, cracks, and lacking joining material, for example. However, the visual inspection cannot give any detail about the mechanical stability of the wall. Moreover, the visual inspection is also not capable to determine whether the seeping-water marks were caused by a past issue before the partial renovation, or if that issue is still existing. In Fig. 4. (b) we present the P-wave velocity tomographic result for the wall. It is clear that the wall has anomalously low P-wave velocity where the visual inspection had highlighted the seeping-water marks (between 15-24 m). Other parts with similarly low velocities can be spotted, suggesting an elevated moisture content of the masonry. Furthermore, the left side of the image shows a zone with P-wave velocities above 1200 m/s. This zone of (relatively) high velocities correlates well with the previously renovated part. It is interesting to note that, although the renovated zone on the right side shows somewhat elevated velocities when compared to the zone with seeping-water marks, these values are still below the values corresponding to the other renovated zone on the left.

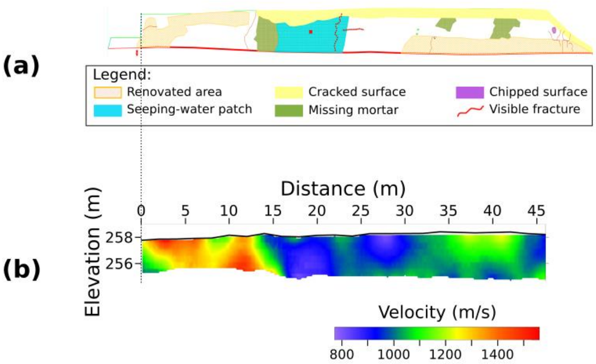

Figure 4. Example for the comparison of (a) visual inspection of a retaining wall with (b) P-wave seismic tomographic result.

As noted above, the P-wave velocity can also be related to the mechanical properties of the wall. That is, the obtained velocities can be used to characterize the strength of the wall too. Because there are still many opportunities to develop high-fidelity relations between seismic velocities and geotechnical parameters to characterize the strength of retaining walls [2], we often rely on the measured P-wave velocities to determine the current state and strength of the walls. The relationship between P-wave velocities and structural strength is discussed, for example, in [3]. Although different geophysical projects require somewhat different frequencies to use, P-wave measurement procedures do not differ from each other significantly. Thus, it might be interesting to compare the seismic velocities determined for different investigated structures in the last few years. In Fig. 5. we compare the propagation velocity of seismic waves for some of our projects in the last few years. We can see that the higher the strength of a structure, the higher the seismic velocities are. Moreover, as in the case of the Sopron Fire Tower stone wall, we can even monitor the rehabilitation of a structure by repeating the same seismic survey in time: the initial seismic inspection determined a velocity below 2000 m/s, while the same wall shows significantly higher values after the injection of the detected voids. Looking back at the seismic velocities of the investigated structure in Fig. 4., it can be stated that even the renovated parts belong to low strength values.

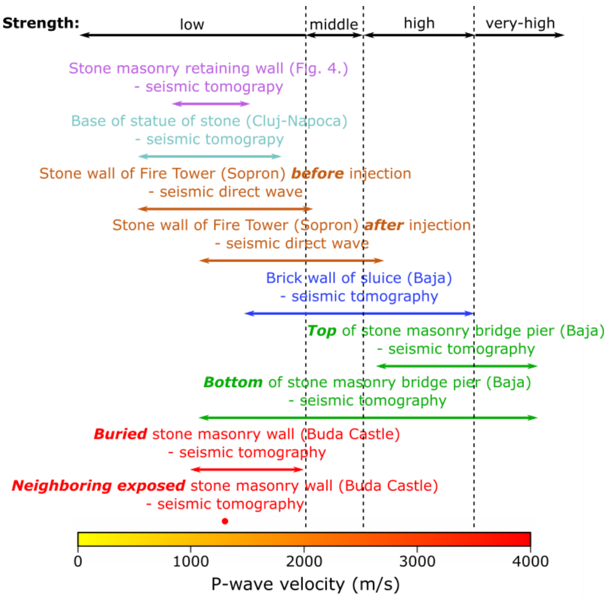

Figure 5. Comparison of the strength after [3] of different investigated masonry walls and corresponding measured P-wave velocities.

3.2. Field examples for gabion walls

In the case of gabion walls, the aim of the geophysical investigation is different from what we have seen for gravity retaining walls. Namely, we usually do not investigate the gabion wall itself, but we focus rather on the backfill and/or the soil below the gabion wall. For these purposes, we often rely on the seismic method, as it is better suited for the task than other geophysical methods like the GPR. Again, in the optimal case, it would be good to measure both P- and S-waves, but for soil characterization mostly the S-waves are used. The main reason for that is, S-waves have a close connection to shear strength, which plays an important role in soil stability investigations.

In Fig. 6., we present an example where the backfill of a gabion wall was inspected with S-wave seismic measurements. The wall is located in Hungary and is often heavily loaded by vehicles. Seismic waves were generated with a sledgehammer and an S-wave seismic source plate, and S-wave geophones recorded the incoming waves along the survey line, denoted with an orange arrow in Fig. 6. (a). After the field survey, S-wave velocities (Fig. 6. (b)) were used to compute both the maximum shear modulus (Eq. 4.) as shown in Fig. 6. (c), as well as a kind of pseudo-SPT(N) value with the following relation for sandy-soil materials after [4]:

$$V_S = 60 \cdot SPT(N)^{0.4} \quad (5)$$

as shown in Fig. 6. (d). These results of the seismic measurements have shown the weak zones of the backfill material, providing crucial input data to civil engineers before the reconstruction of the wall.

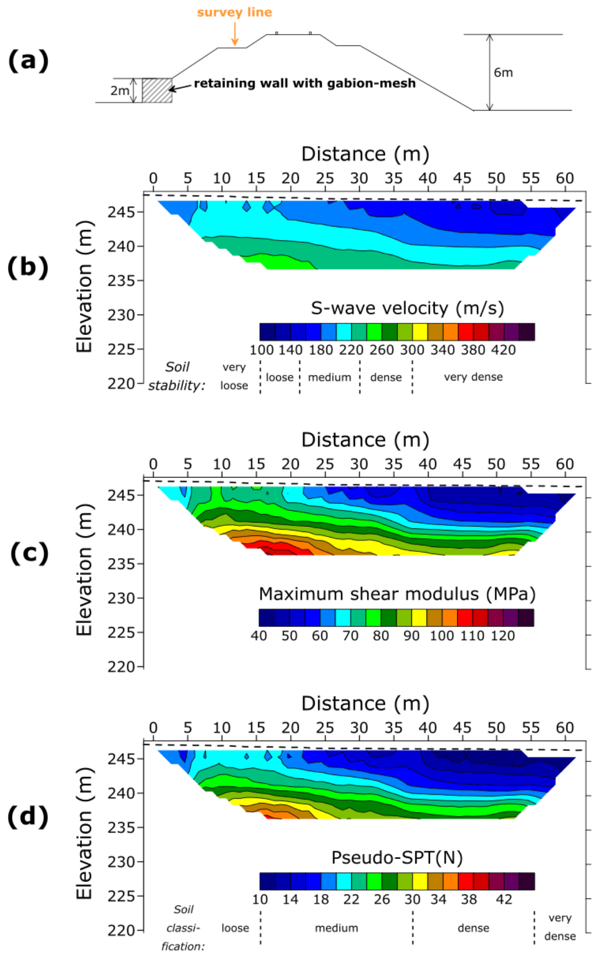

Figure 6. Example of a gabion wall: (a) schematic figure of the wall and the survey line; (b) tomographic seismic S-wave velocity image; (c) calculated maximum shear modulus values; (d) calculated pseudo-SPT(N) values after [4].

4. Direct current (DC) electric method

Electric imaging can detect changes in electric resistivity of the subsurface. Since electric resistivity depends on various parameters, such as mineral content, porosity, degree of water saturation, geoelectric methods can also provide crucial information about retaining walls, or more precisely about their surroundings. Table 2. shows the electric resistivity values of some typical backfill materials after [5]. As we can see, there is not only a significant difference in the resistivity of the different materials, but the same material shows very different values depending on its moisture/water saturation level.

DC electric resistivity measurements use electrodes to inject a direct current into the soil through metal electrodes. Then potential electrodes are used to measure the voltage difference between them due to the injected current. From the current and voltage readings, the resistivity of the subsurface can be computed. Depending on the purpose of the geoelectric investigation, different electrode spacing and layout may be necessary [5].

Table 2. Resistivity of some typical backfill materials after [5]

Material	Resistivity (Ωm)
Dry gravel	1 000 – 10 000
Water-saturated gravel	50 – 1 000
Dry sand	100 – 1 000
Water-saturated sand	20 - 100
Clay	2 – 20
Chalk	100 – 5 000

Since electrodes are physically hard to deploy on gravity retaining walls themselves, as well as the gabion mesh is not suitable for electric measurements due to its conductive wire cage, DC methods can be used to characterize rather the backfill of retaining walls.

4.1. Field examples

Here, we present an example of a DC electric resistivity survey to characterize the backfill material of a gravity retaining wall made of concrete in Hungary. The goal of the geophysical investigation was to determine if the wall still has sufficient water drainage. In Fig. 7. we present the resistivity map inverted from the survey data. In general, the resistivity of the backfill is higher than 200 Ωm, therefore it most probably consists of dry soil and/or gravel with a mild moisture level. We can separate two zones along the section: at horizontal distances below 16 m, there is a zone with rather low resistivities, while the zone to the right shows significantly higher values in the elevation range of 118 and 122 m. The reason for the low resistivity zone is that the corresponding weep holes are clogged and are not functioning anymore, therefore the rainwater cannot drain and it accumulates in place. On the contrary, the zone to the right with high resistivity values has still intact and functioning weep holes, which can sufficiently drain the backfill behind them. These conclusions were supported by the visual inspection of the retaining wall. In Fig. 7. we also show two photos corresponding to these zones. The photo on the left shows no significant mark of flowing water close to the weep hole, that is, the hole is probably clogged, in accordance with our previous observation of low resistivity due to the large amount of accumulated water. On the contrary, the photo on the right shows some significant marks of recent water flowing coming from the weep hole, explaining the observed high resistivity values in the corresponding backfill zone with sufficient drainage.

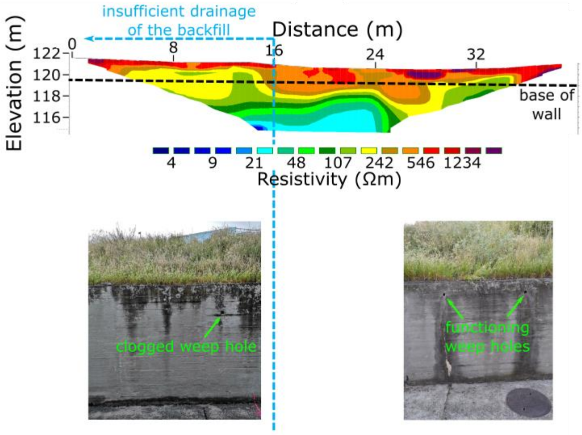

Figure 7. Example for the geoelectric DC survey of retaining walls to investigate the water drainage of the backfill: (a) inverted results showing the resistivity values; (b) a section of the wall with clogged weep holes and insufficient drainage; (c) another section of the wall with functioning weep holes and drainage.

5. Conclusions

There is widespread interest in the inspection of retaining walls considering their current state, structural health, and structural integrity. Some potentially serious damages to these structures can be identified by visual inspection already. However, as shown above, geophysical methods have the means to provide significantly more information than what can be seen from the front face of a wall.

We have showcased GPR, seismic, and DC electric real-life examples, where these methods helped us to identify potential issues, such as, for example, cracks and voids, which are not (yet) visible on the outside. Moreover, geophysical methods can also shed light on the possible causes of these potentially serious issues, for example, accumulated water behind clogged weep holes.

When using geophysics to assess the condition of retaining walls, it is important to take into consideration the type of retaining wall, as well as its surroundings. The reason for that is, some geophysical methods are better suited than others to investigate a certain type of retaining wall, and similarly, different parts of a retaining wall structure requires a different approach (e.g., investigation of the backfill requires rather seismic and/or DC electric measurements than GPR).

We have also seen that there is still a lot of research and development to be done to utilize the full value of various geophysical methods in the engineering assessment of retaining walls. For example, future works should focus on an elaborated relationship between seismic velocities and structural strength.

6. References

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