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HIGH-SPEED TRAINS – MAGLEV TRAINS

Abstract:

The development of megacities, with a large population, imposes increasing mobility in order to maintain the economic and social development. There is a great necessity for a contemporary and new infrastructure at the urban, suburban, intercity, and international level. At the same time, there is also a need to improve transport in terms of environmental protection, to reduce effects such as noise, pollution, and congestion. The latest researches show that by 2050, carbon dioxide (CO_2) emissions need to be reduced by 75%. This reduction can be achieved only by applying new technologies of transportation systems. One of these technologies, which is shown in this work, is the Maglev system for trains of high speed.

Keywords: infrastructure, conventional rail, maglev system, route, levitation

ВОЗОВИ ВЕЛИКИХ БРЗИНА – МАГЛЕВ ВОЗОВИ

Сажетак:

Развој великих метропола, са великим бројем становника, захтева све већу мобилност како би се одржао економски и друштвени развој. Због тога постоји велика потреба за модерним и новим ифраструктурама на урбаном, приградском, међуградском и међународном нивоу. Истовремено постоји и потреба да се саобраћај побољша са аспекта очувања животне средине, да се смање ефекти као што су бука, загађење и загушење. Најновија истраживања показују да до 2050. године треба смањити емисију угљен-диоксида (CO_2) за 75%. То смањење је могуће извести само применом нових технологија транспортних система. Једна од тих технологија, која се се приказује у оквиру овог рада, јесте Маглев систем за возове великих брзина.

Кључне речи: инфраструктура, класична железница, маглев систем, траса, левитација

1. INTRODUCTION

Contemporary development of megacities and associated increasing urbanization have imposed heavy transportation conditions, as well as harmful effects upon environment [1]. Considering the results of recent studies, road transport prevails in the global transport industry with a percentage share of around 35%. On one hand, road transport contributes around 73% of total carbon dioxide (CO_2) emission resulting from the transportation, and on the other one, it consumes more than 75% of total transport energy demand [3]. According to this, there is a growing necessity for establishing clean and efficient transit systems. When it comes to the rail transportation industry, it has become apparent that this type of transportation has the capability to cope with the expanding transport network; however, on-wheel railways worldwide fulfill 60% of their total energy demand using petroleum-based products, which emphasizes the need for electrification of railways and for improvement of their technological performance [3]. These facts have attracted the attention of the researchers and manufacturers worldwide and given rise to the development of rail technology based on magnetic levitation – the so-called Maglev system. This railway system is a fully electrified system, which is in agreement with the renewable energy resources without any technological modifications, thus providing sustainability of the system [1-3].

The Maglev system use electricity, which has recently been increasingly sourced from sustainable alternative energy sources, much less from fossil fuels. In addition, the Maglev system uses less energy than other railway systems and is therefore more economical. Moreover, research has shown that the energy consumption of electric cars (whose technology is similar to the Maglev system) would be three times higher for the same transport route. On the other hand, the Maglev system is more economical for mass-transport, without causing any negative environmental consequences (noise, pollution, etc.)

Magnetic levitation represents a contemporary and highly-advanced technology of various uses and advantages. One of these is the lack of contact, thus contributing to elimination of wear and friction, and by that, to increase of efficiency, decrease of maintenance costs, as well as to increase of the service life of the system.

The main structural element of the Maglev system is the guideway, which supports and guides maglev trains to move over it and transfers the applied vehicle load to the ground. This element has big share of the system costs. There is a single- or double-track guideway. In addition, there is an option a guideway to be placed at-grade (ground-level) or to be elevated on columns with concrete, steel, or hybrid beams, in which case it occupies the least amount of land on the ground and avoids obstacles that exist along the route. In order to secure the safety of the Maglev trains, it is needed to provide no intersection between guideway and other forms of traffic routes, which could be assured by using elevated guideways. In contrast to classic-type railroad tracks, considering the Maglev-system guideways, a necessity for ballast, sleeper, rail pad, and rail fastenings to stabilize the rail gauge is avoided.

Considering the analysis and design of guideways, the most significant part the engineers should be aware of is structural loading, consisting of a dead load induced from its own weight, as well as live loads including the vehicle loads. In order to take into account the dynamic interaction between the guideway and the vehicle, the live load is multiplied by a dynamic amplification factor. Other types of loads, such as wind- and earthquake-induced loading, should also be taken into consideration.

The latest researches show that by 2050, carbon dioxide (CO_2) emissions need to be reduced by 75% [4]. This reduction can be achieved only by applying new technologies of transportation systems, such as the Maglev system of high-speed trains.

Today, several commercial maglev-system lines are in operation worldwide: the railway line Shanghai–Pudong Airport, the line from Incheon International Airport to the station Iongiu in South Korea, the Tobu–Kiurio Line (the so-called Linimo) in Japan, and the line from the Changsha Huanghu International Airport to the Changsha South Railway Station. The Maglev system as an urban transportation system, with a limited speed of up to 100 km/h, was applied so far only in Japan. Due to the large investment of construction and short distances, the Maglev system will have less application in urban transportation.

Analyses of the use of the Maglev system lines have shown their justification from all aspects, particularly the economic one. With this in mind, nowadays, an increasing number of research studies are underway considering the construction of new lines of this type of system in the world.

Some recent studies have indicated that, for the reason of high speed of transportation vehicles, the operation safety of Maglev train is influenced by the differential settlement due to different properties of soil layers, and by that, the operation of the Maglev train could contribute to increasing of the soil drowning.

Taking all into account, the Maglev system is believed to be capable of assuring safe and comfortable transport of passengers in the future.

2. COMPARISON OF RAILWAYS OF THE CLASSICAL TYPE AND OF THE ADVANCED MAGLEV SYSTEM

This section is dealing with the most important differences between the standard rail system and the Maglev system considering several points of view.

2.1. Vertical and lateral guidance

2.1.1. Conventional railway

Considering the traditional rail, there are both vertical and lateral guidance. The system of standard railways has a disadvantage of being very sensitive to geometric precision. However, there is a number of its advantages such as low resistance, especially at low speed. The force transmitted through the contact surface is 50-100 kN/cm^2, which is distributed to the ground through a series of components, such as rails, sills, drapes, etc.

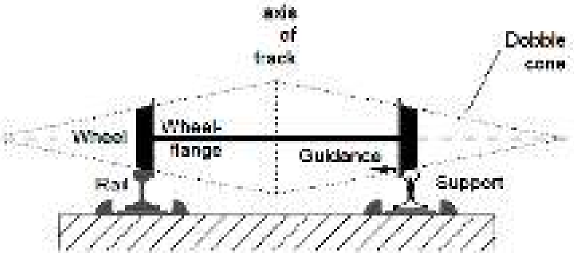

Figure 1 *Vertical and lateral guidance of the conventional rail [5]*

2.1.2. Maglev system

In case of the advanced Maglev system, vertical and lateral guidance is provided by levitation system without contact, which is based on the principle of magnetic field. In comparison with the traditional rail, the pressure between vehicle and infrastructure in this case is significantly reduced.

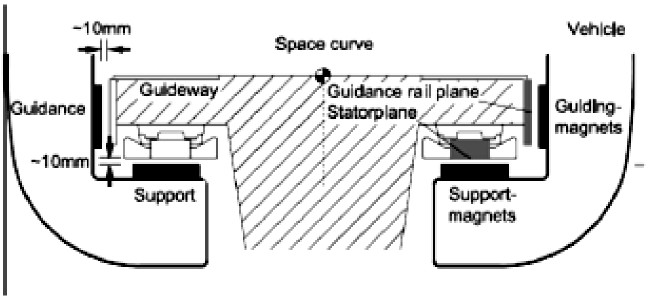

Figure 2 *Vertical and lateral guidance of the Maglev system [5]*

2.2. Drive

2.2.1. Conventional railway

Torque is transmitted to the rail over the contact surface of the wheel and the rail. The transfer of driving force by this mechanism requires a sliding movement in one part of this area (in the full area when the gliding conditions have been reached). This sliding movement creates wear. The force advantage depends on the wheel load.

2.2.2. Maglev system

The drive force is out of contact, which is achieved by creating electromagnetic force without mechanical movement and without wear. In case of low-speed maglev trains, the active part of the engine is located inside the vehicle and energy is powered by the energy transfer system. In case of high-speed maglev train, the active part of the engine is mounted on infrastructure, which facilitates contactless transmission of power to the vehicle.

2.3. Power supply

2.3.1. Conventional railway

Considering European countries, the voltages in electric traction occurring on contact networks are DC 3kV and AC 25kV/50Hz, which is also the most widespread locomotive power supply system. Energy is supplied from electric traction substations (EVPs) located along the contact grid.

2.3.2. Maglev system

Power is supplied by substations, which contain all the necessary components for the drive, power, and operating system of the Maglev technology, whereby the maximum distance between two substations on the route attains about 50 km.

2.4. Communications and operational control

The essential differences considering the standard rails and the advanced Maglev technology are attributed mostly to operational control, which allows the Maglev system to be fully automated. Communications technology could be interoperable, or content of information is different.

3. MAGNETIC LEVITATION

Magnetic levitation is an advanced technology, which is based on magnetism and in which one object hovers (levitates) over another without any mechanical support, but only with the help of a magnetic field. Accordingly, the effect of gravitational force is canceled out by the action of an electromagnetic force of the same intensity and direction, but in the opposite direction, thereby achieving hovering. With an aim to provide stabilisation of this system, electronic stabilisation of magnetic levitation is being used [1].

3.1. Electromagnetic suspension system (ems)

In order to achieve magnetic levitation, the design based on magnetically attractive forces between the guideway and the on-board electromagnets installed below the guideway is being used in this Maglev system, which accomplishes levitation even at zero speed. This system uses standard electromagnets that conduct in the presence of electric power supply only, which results in magnetic fields of comparatively lower intensity inside the passenger vehicles, and by that makes the travel for the passengers more comfortable.

On the other hand, however, lower intensity of magnetic field induces an appearance of a levitation air gap of 1 cm, whose controlling becomes more and more inconvenient with increasing the vehicle velocity. Therefore, the EMS system appeared to be suitable for the case of low- to medium-speed vehicles. In Shanghai, Korea, and Japan this system is used with the levitation and guidance circuits completely integrated (Fig. 3). In Germany, the EMS technology is used with the levitation and guidance circuits completely separated, which makes it suitable for high-speed operation due to the absence of interference between the two circuits [9-11].

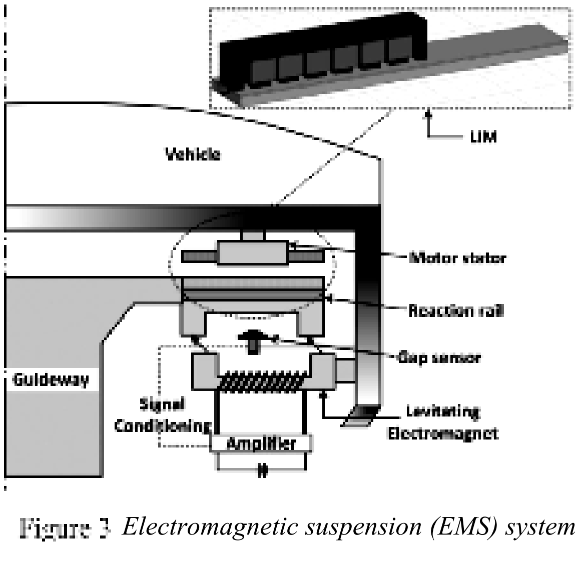

Figure 3 *Electromagnetic suspension (EMS) system [1]*

3.2. Hybrid electromagnetic suspension system (hems)

This system represents a modification of the previously presented EMS system (Fig. 4) and is established on an employment of permanent magnets and electromagnets, in order to reduce the electric power consumption of the conventional system and to achieve larger air gaps. At the beginning of a drive, the system uses both the electromagnets and permanent magnets to generate levitation. After accomplishing a steady-state air gap, the permanent magnets solely starts levitating the vehicle, thus cancelling out the power of the electromagnets. The permanent magnets produce a constant magnetic flux. Hence, in the HEMS system, the necessary air gap control is achieved by adjustment of the electromagnet's excitation, so the requirement for a controllable input source of greater variation is of paramount importance for exciting the electromagnets [12,13].

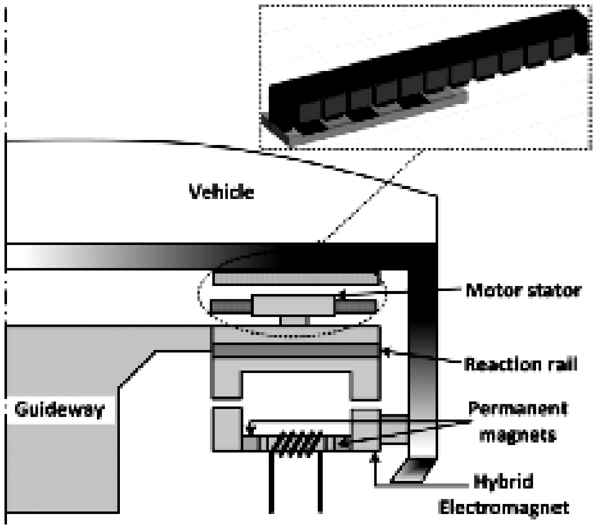

Figure 4 *Hybrid electromagnetic suspension (HEMS) system [1]*

3.3. Electrodynamic suspension system (eds)

In the EDS technology, levitation is achieved by usage of magnetic repulsive force (Fig. 5), which is being generated by moving forward of on-board magnets with the vehicle over the guideway that consists of inductive coils or conducting sheets, owing to interactions of on-board magnets with the currents induced in the guideway coils. The required levitation of the vehicle is provided by this repulsive force, and the levitation magnitude that can be achieved is of up to 10 cm. This system, however, suffers from the weak point, which is related to the requirement of rubber tires on which the train must roll initially until it reaches a lift-off speed of about 100 km/h. Furthermore, the EDS system employs superconducting magnets, which are super-cooled at frigid temperatures using a cryogenic system [1].

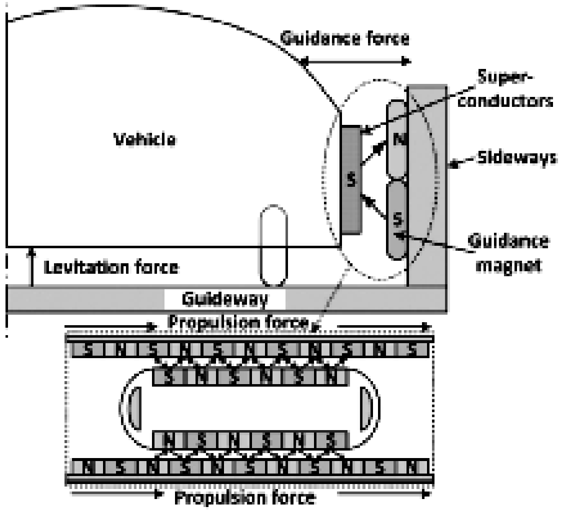

Figure 5 *Electrodynamic suspension (EDS) system [1]*

3.4. Permanent magnet – electrodynamic suspension system (pm-eds) – “inductrac” system

This system stands for a modification of the aforementioned EDS system, and is based on application of permanent magnets at room temperature, arranged in the form of a Halbach array (Fig. 6). Opposite to the EDS technology, this system does not require any super-cooled magnets, thus neutralising any cryogenic requirements. On the other hand, however, the PM-EDS system uses auxiliary wheels for acceleration of the vehicle until the moment it achieves some initial take-off speed, after which it starts levitating. This system has been under trial by General Atomics, USA, with suspension magnets separated from propulsion magnets [1].

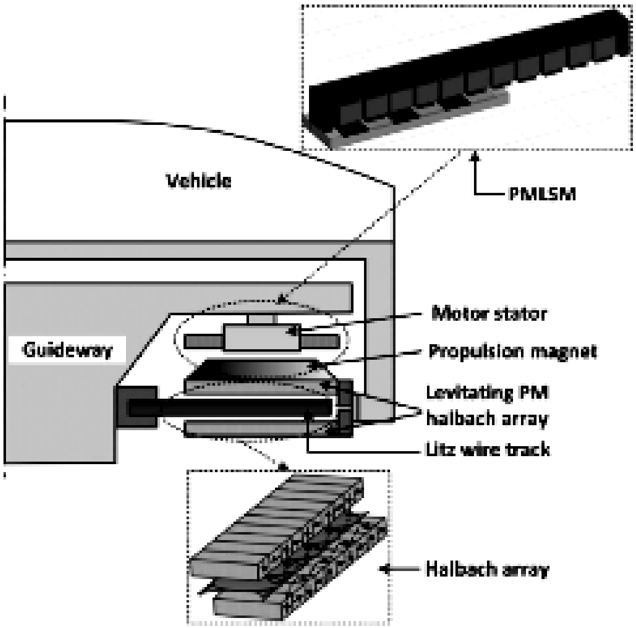

Figure 6 *Permanent magnet –electrodynamic suspension (PM-EDS) system [1]*

4. TECHNICAL PROPERTIES OF THE ROUTE

Considering the advanced Maglev railroad-track technology, several types of guideways can be distinguished [7], depending on certain configuration:

- At-grade guideway;
- Elevated guideway: Type A - single column;
- Elevated guideway: Type B - straddle bents;
- High-column bridges;
- Shallow tunnels: Type A;
- Deep tunnels: Type B **.**

4.1. Ground-level guideway

This configuration (Fig. 7) is predominantly used in open, flat rural regions, where the guideway can be placed at grade, along with avoiding intersection with roadways, utilities, streams, and other topographical shapes. Here, the precast concrete beams with spans up to 7.62 m are used, which, if required, can be curved and/or elevated in order to follow acceleration and alignment conditions.

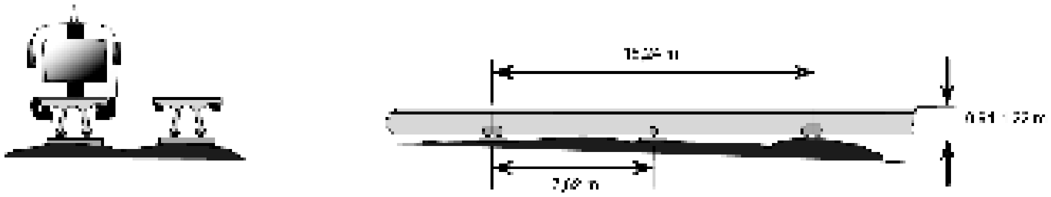

Figure 7 *Ground-level guideway configuration [7]*

4.2. Elevated guideway

The elevated-guideway configuration (Figs. 8 and 9) appeared to be applicable in congested urban areas, in which case columns can be placed in the median of a freeway and the guideway can travel over parkways, intersecting roadways and other facilities. The precast concrete girders, with spans up to 30.48 m, are similar to the ones tested at the Transrapid Test Facility in Emsland, Munich. The elevated guideway can also be curved and elevated in order to match geometric and lateral acceleration requirements. These beams are supported with single column (Type A, as shown in Fig. 8) or two-column (Type B, as shown in Fig. 9) straddle bents with heights of up to 19.81 m.

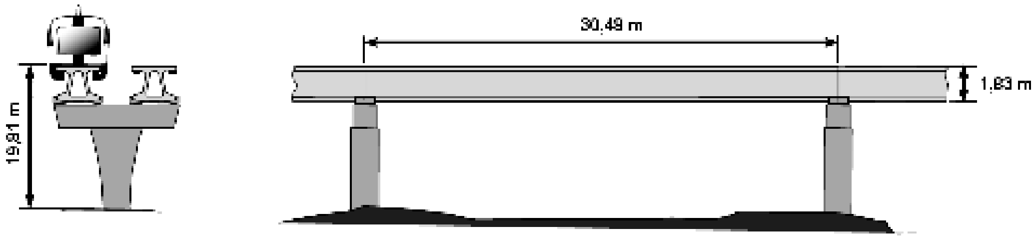

Figure 8 *Elevated-guideway configuration: Type A - single column [7]*

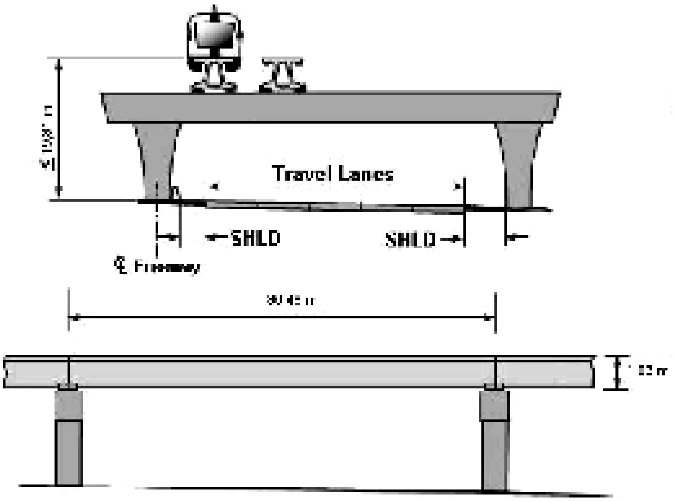

Figure 9 *Elevated-guideway configuration: Type B - straddle bents [7]*

4.3. Bridge structures

This configuration is needed to apply for spans over 30.48 m or column heights that exceed 19.81 m, which is a common situation in remote and mountainous areas. The bridge structures are usually made of precast concrete segments, constructed using the balanced cantilever method. The maximum size of span for this type of construction is assumed to be of about 60 m.

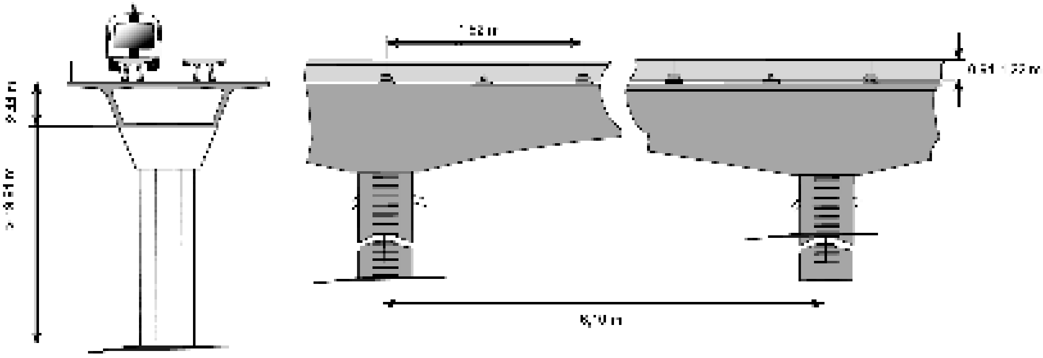

Figure 10. *Bridge-structure configuration [7]*

4.4. TUNNEL STRUCTURES

Considering hilly and mountainous terrains, design of tunnels will be suitable solution in case when satisfying longitudinal slope conditions is needed. There exist two types of tunnel structures: Type A considering shallow-laid tunnels (Figs. 11 and 12) and Type B including deeply embedded tunnels (Figs. 13 and 14). When it comes to deeply embedded tunnels, a design of the third auxiliary tunnel facility is foreseen for the purpose of the operation of the two main tunnels.

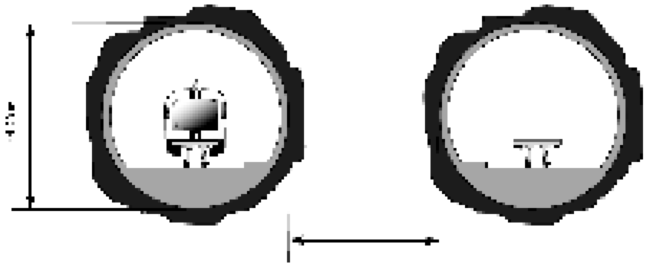

Figure 11. *Figure 11. Shallow-laid tunnels – Type A [7]*

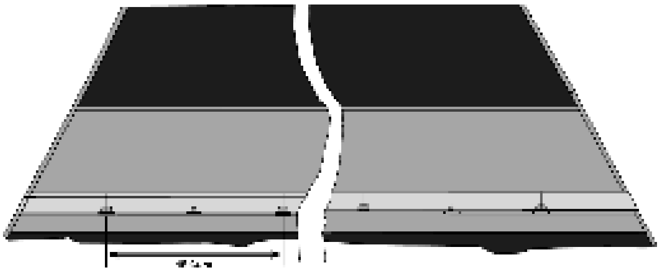

Figure 12. *Figure 12. Shallow-tunnel elevation – Type A [7]*

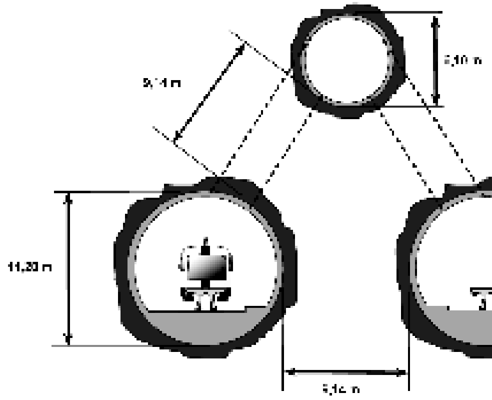

Figure 13. *Deeply embedded tunnels – Type B [7]*

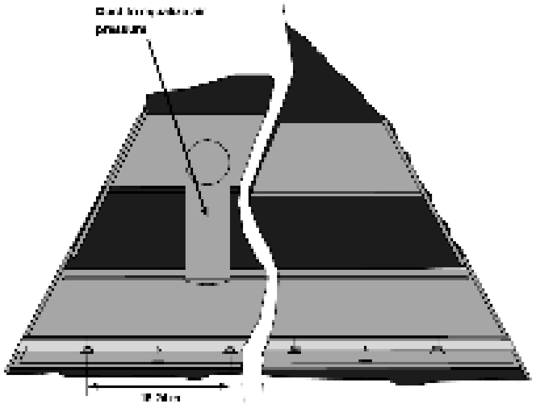

Figure 14. *Deep-tunnel elevation – Type B [7]*

5. GEOTECHNICAL PROPERTIES OF THE TERRAIN ALONG THE RAILWAY ROUTE

Taking into account that the Maglev advanced technology is characterized by very high speeds of transportation vehicles, the safety of the system considering operational stage should be of utmost importance. Namely, for the reason of high speed of transportation vehicles, the operational safety of Maglev train is highly influenced by the geotechnical properties of soil layers within terrain along the railway route.

Construction of the Maglev system is quite expensive, and consequently maintenance works are minimized. Accordingly, special attention must be paid to the construction process. The most sensitive part of this system is the connection of the structure to the ground. Settlement of the structure can cause deformation of the guideway, and thus to endanger the functioning of levitation. According to the Chinese high-speed railway regulations (including the Maglev system), the permissible settlement of the structure is 20 mm and the safe differential settlements (the difference in settlements of the points of the structure) are 5 mm. Any settlement, and in particular differential settlements, oversizing recommended allowable values in the operation stage, would result in disruption of traffic and major investment activities and, consequently, in enormous economic losses.

In order to prevent settlements and, by that, endangerment of the structure, extensive and detailed geotechnical investigations should be carried out. This is the best way to prevent subsidence, because a comprehensive analysis of the survey results will yield an optimal foundation solution and a correct choice of the corresponding ground stabilization technique to improve the soil properties if needed. A lack of systematic and precisely conducted geotechnical investigations will inevitably result in unsafe settlements and damage to the structure, thus leading to costly remedial measures.

In one of the recent studies [8], soil displacement monitoring (i.e., soil deformation along the route and soil settlement) was analyzed in detailed way for the existing Maglev route in Shanghai, overlying soil layers of poor bearing capacity. In addition, with an aim to investigate the settlements induced by the Maglev system and to improve the settlement monitoring, five soil observation stations along the route were installed on the Shanghai section. A typical geological profile with the layout of the layers and soil composition is presented in Fig. 15, whereby it should be emphasized that the thicknesses of the layers are different along the railway route, and by that, bellow the considered observation stations, for which the results of the performed measurements are depicted in the diagrams (Figs. 16-20). The results have revealed that the operational safety of high-speed Maglev train is strongly influenced by the differential settlements induced by diversity in properties of soil layers, whereby the operation of the Maglev train may induce a significant subsidence of the ground, i.e. a gradual shaking of the foundation can lead to damage if the sizing is uneven. The results also indicated that ground settlement has adverse effects on the structure above the foundation, due to which the operational life of the structure can be significantly reduced.

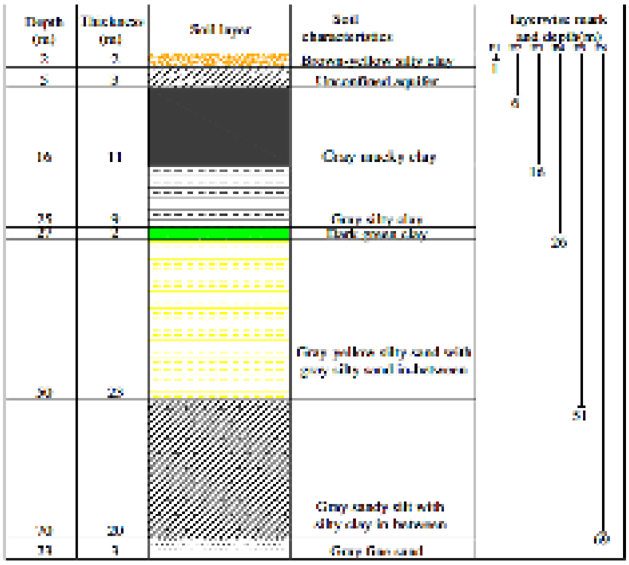

Figure 15. *Typical geological profile of the terrain along the Maglev route in Shanghai [8]*

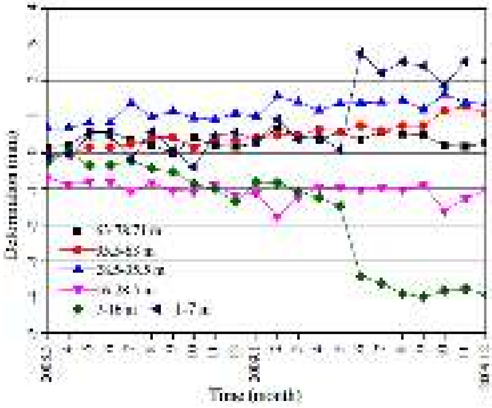

Figure 16. *Settlement at different depths as a function of time: station P1 [8]*

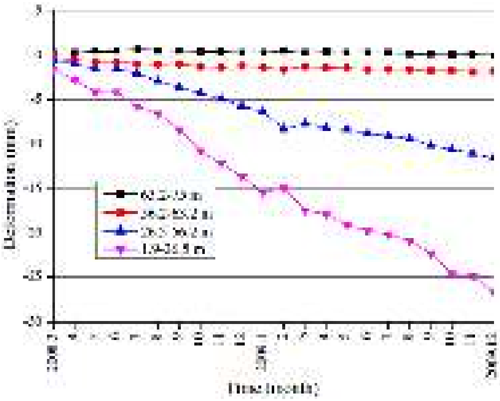

Figure 17. *Settlement at different depths as a function of time: station P2 [8]*

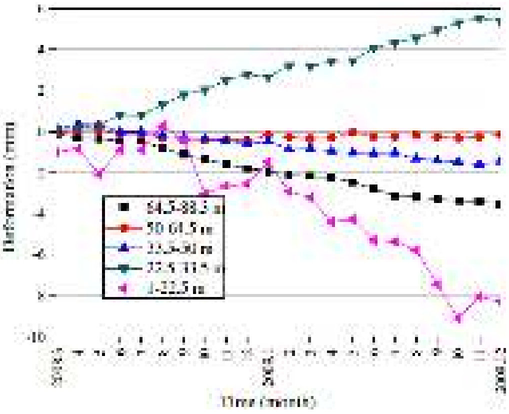

Figure 18. *Settlement at different depths as a function of time: station P3 [8]*

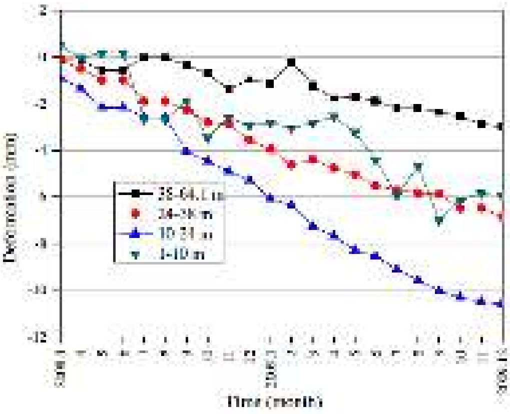

Figure 19. *Settlement at different depths as a function of time: station P4 [8]*

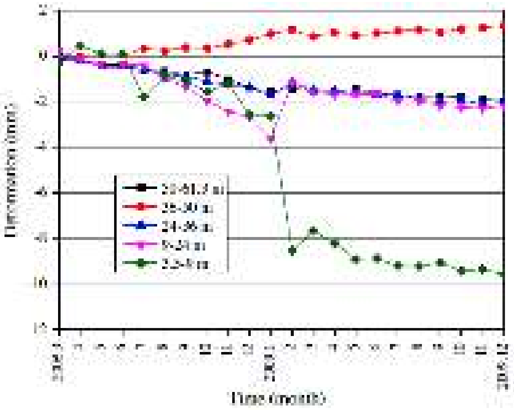

Figure 20. *Settlement at different depths as a function of time: station P5 [8]*

6. ADVANTAGES OF THE MAGLEV TECHNOLOGY OVER CONVENTIONAL SYSTEMS

The main advantages of the advanced Maglev technology over other types of transportation systems, and in particular over conventional railway system, can be summarized as follows:

- The Maglev system does not make noise; it is more economical and uses less energy than any other rail system.
- The possibility of the train falling out of the guides does not exist, and comfort is supreme at all speeds.
- The system is characterized by low consumption of required space for construction.
- The road guide takes less space in comparison with standard stripes and can be flexibly adjusted to accommodate existing natural areas and terrain forms along the route of the guide due to the small diameter of the curvature and high degree of climbing ability up to 10%.
- Due to a small embankment and a cutting, the nature disturbances are set to a minimal level.
- The Maglev train load is equally distributed across the guides (i.e., there is no point load), thus resulting in less static and dynamic loadings over the entire speed range, and therefore, less voltage on the guides.
- Maglev trains use small amount of energy, whereby all systems are powered by the harmonic oscillations of the magnetic field of the linear motor stator located on the line.
- If a power failure appears, the trains are supplied with batteries that maintain levitation for a certain period of time.
- The Maglev vehicle does not rely on rails; actually, it floats over an average reliable distance of about 1 cm from its guides owing to a highly reliable electronic control system.
- The distance between the top of the guide and the underside of the vehicle during contactless and frictionless hovering is 15 cm; this has the advantage of passing over some smaller objects or a layer of snow.
- The Maglev system is characterized with high acceleration and braking ability;
- The system requires less staff to operate and maintain, as well as fewer spare parts and materials, thus resulting in management costs that are less than those of rail systems of classic type. In addition, comfortable travel results in shorter travel times and is not too expensive.
- Space and land beneath elevated guideways can be used, for example, as land for agriculture, construction, etc.

7. CONCLUDING REMARKS

The development of large metropolises involves an increase in the number of citizens. The need to transport a large number of passengers, as well as goods, imposes the development of transportation systems such as the high-speed Maglev railway system. Magnetic levitation, i.e. contactless and frictionless movement of vehicles, is a new and advanced technology that is proved to have the potential to become a reality and is believed to be capable of assuring safe and comfortable transport of passengers in the future. It has a number of advantages over traditional systems, such as frictionless hovering, reduced noise, more comfortable driving, increased safety, independence from weather conditions, ability to cope with higher climbs, usage of narrower stripes mounted above the ground that do not interrupt the terrain, etc.

Just recently, owing to the aforementioned advantages, the Maglev system has been applied in some of the most developed industrial countries in the world. The applications of the Maglev system are justified for transport of a large number of passengers and goods from one megacity to another (which are often several hundred kilometers away), as well as for distances from large metropolitan areas to suburban airports (especially those for overseas traffic). Due to the large investments for construction and short distances, the Maglev system have less application in urban transportation with a limited speed of about 100km/h.

Maglev trains are considered to be an alternative to short- and medium-range aircraft (up to 1000 km) in the future. Even though train speeds are less than those of aircraft, considering the distance of the airports from the metropolitan centers, travel times are considerably shorter.

Nowadays, numerous researches are being performed considering the characteristics of magnetic levitation with an aim to improve the existing Maglev system. Essential problems could be considered to be solved, since a lot of has been done on the development in technological sense. However, the fact that high initial costs of construction are imposed by this technology, due to very complex computer systems for levitation management, could be considered as its essential shortcoming. This makes the construction of this type of railways suitable only in conditions of a large number of passengers and goods. The maintenance costs, on the other hand, considering both trains and tracks, are of lower value.

Nevertheless, taking into account all the former facts, numerous advantages of the Maglev technology are prevailing and this system can make a huge contribution to our everyday life.

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LITERATURE

[1] N. Prasad, S. Jain, S. Gupta, “Electrical components of Maglev systems: emerging trends”, Urban Rail Transit, vol. 5, no. 2, pp. 67-79, 2019.

[2] Passenger Department. “Passenger activities at UIC”. International Union of Railways (UIC). https://uic.org/IMG/pdf/brochure_passagers.pdf , 2019.

[3] Passenger Department. “High speed rail fast track to sustainable mobility”. International Union of Railways (UIC). https://uic.org/IMG/pdf/uic_high_speed_2018_ph08_web.pdf , 2018.

[4] Railway Handbook. “Energy consumption and CO_2 emissions focus on passenger rail services”. International Energy Agency (IEA) and International Union of Railways (UIC). https://uic.org/IMG/pdf/handbook_iea-uic_2017_web3.pdf , 2017.

[5] A. Cassat, V. Bourquin, “MAGLEV – Worldwide status and technical review”, in Proc. Électrotechnique du Futur, December 14–15, 2011, Belfort.

[6] M. Saied, M. Al-Shaher, “Harmonic distortion assessment and minimization for railway systems”, Electr Power Compon Syst, vol. 37, no. 8, pp. 832-846, 2009.

[7] SANDAG, “Maglev Study Phase 1”, Final Report, 2006, p. 185.

[8] Z.D. Zhen-Dong Cui, Q. Qiang Yuan, “Study on the settlement caused by the Maglev train”, Nat Hazards, vol. 75, pp.1767-1778, 2015.

[9] P. Holmer, “Faster than a speeding bullet train”, *IEEE Spectr,* vol. 40, no. 8, pp. 30-34, 2003.

[10] R.J. Kaye, E. Masada. “Comparison of linear synchronous and induction motors”. Urban Maglev Technology Development Program Colorado Project. https://www.codot.gov/programs/research/pdfs/2004/inductionmotors.pdf , 2004.

[11] J. Meins, L. Miller, W.J. Mayer, "The high speed Maglev transportation system TRANSRAPID", *IEEE Trans Magn,* vol. 24, no. 2, pp. 808-811, 1988.

[12] Y.K. Chin, J. Soulard, "A permanent magnet synchronous motor for traction applications of electric vehicles", *in Proc. IEEE International Conference on Electric Machines and Drives "IEMDC 2003"*, June 1–4, 2003, Madison, USA.

[13] W. Zhang, J. Li, K. Cui, P. Zhang, "Design of magnetic flux feedback controller in hybrid suspension system*", Mathematical Problems in Engineering*, pp. 1-7, 2013.