Structural Design Ingenuity

A Critical Component for a Sophisticated Science Building
University of Scranton – Loyola Science Center

By Alvin P. Tabar, P.E.

In fall 2011, Phase 1 of the Loyola Science Center (LSC) at The University of Scranton in Scranton, Pennsylvania, opened its doors, transforming the university's science, technology, engineering, and mathematics (STEM) learning environment. The new 150,000-gross-square-foot facility is equipped with the latest technologies to support STEM pedagogy, and provides distinctive spaces for teaching, learning, and research within and across disciplines. Given the high level of environmental control required by sophisticated scientific equipment, structural and foundation designs have become increasingly complicated, while the characteristics of the supporting soil have only limited scope for manipulation. Providing a safe and efficient interface between science facilities and the soil media therefore requires structural engineering ingenuity. For the LSC, these design complexities were exacerbated by existing site conditions, where abandoned coal mines below the site and nearby railroad traffic presented extraordinary challenges.

Abandoned Coal Mines

The City of Scranton, known today as the home of the fictional Dunder-Mifflin paper company in the NBC sitcom, *The Office*, was once the center of Pennsylvania's anthracite coal mining industry. When oil and natural gas replaced anthracite coal as a preferred energy source, the downfall of the mining industry in Northern Pennsylvania left a city scarred by abandoned coal mines. As soon as buildings started rising above and around these abandoned mines, ground subsidence became a widespread problem as the pillar supports for the roofs and overlying surfaces of abandoned mines began to fail. While such failures are no longer a common occurrence – thanks to the state and federal flushing projects or backfilling efforts that stabilized the ground surface in the late 1970s – underground voids are still present in some areas. Site soil exploration performed by the geotechnical engineering consultant revealed deep underground voids within 100 feet below ground of the proposed LSC, and determined that a potentially 20-foot wide sink hole could develop anywhere beneath the new structure. During early design phases, engineers considered three viable foundation systems to mitigate possible structural failure due to mine subsidence:

- Caissons or conventional spread footings with interconnected grade beams.
- Conventional spread footings after site modifications through grouting of underground voids.
- Mat slab foundation system.

For the LSC, mat slab proved to be most appropriate alternative because of its simplicity, more rapid pace of construction, and the relatively inexpensive cost estimated to be fifty percent less than that of the caisson option.

Mat Slab Foundation System

Every structural problem has a solution, but sometimes the solution to one problem creates its own challenges. Such was the case with the mat slab foundation system for the LSC Project. Mat slab is relatively simple to design using the finite element method (FEM) adopted in most structural concrete design programs like SAFE by Computers & Structures, Inc., which is utilized in the design or RAM Concept by Bentley and a number of other commercially available structural analysis and design software. For a complicated site such as that of the LSC Project, the challenge is in manipulating the supporting natural soil media to achieve the desired engineering properties for a safe and efficient building support. This solution requires a high degree of ingenuity and "engineering judgment" or instinct on the part of the structural engineer.

For the LSC Project, the mat slab foundation mitigated the potential for structural failure due to ground subsidence by acting as a transfer slab bearing on the stable ground left behind around the depression. At the same time, however, it takes up space for under-slab ducts, plumbing, and other services that in conventional foundation construction could otherwise have been easily located between spread footings or pile caps. To make room for these elements, the top of mat slab needed to be dropped three feet below the ground-floor slab. The shallow top of bedrock at this site required rock excavation in some areas, which increased the risk of weakening the roof of the abandoned mines.

Another concern was the subsequent irregularity in the substrata due to the variability of the topography of the top bedrock found in the site, which caused some portions of the mat slab to sit on bedrock and the rest on native soil. Resolving this challenge required a more complex structural analysis, necessitating the use of multiple flexibility coefficients or modulus of sub-grade reactions. To maintain a homogeneous subsoil layer throughout the entire mat slab, modification to the existing site soil condition was required. One option was removing the natural soil portion of the site and infilling cavities with lean mass concrete. This option can provide additional stiffness to the overlying surfaces of the abandoned mines, reducing the risk of ground subsidence, but it requires significant amounts of concrete and the associated cost is considerably high. The alternative was to further undercut the existing substrata, including the bedrock, and backfilling with select structural fill materials up to the desired founding level. While the latter option further increases the required rock excavation and could weaken the roof of the abandoned mines, increasing the risk of ground subsidence, the structural fill layer separating the mat slab from the bedrock serves a double purpose. It not only creates a homogeneous subsoil layer for the mat slab to bear on, it can also produce foundation coupling loss or partial reflection of vibration energy at the interface between the bedrock and the layer of fill materials due to impedance mismatch (different material properties). Foundation coupling loss is essential to mitigating the effect of the other structural issue in the project, "ground-borne train vibration" from nearby railroad traffic. Adopting the latter site modification option in the LSC project contributed to reducing construction cost by avoiding otherwise costly special vertical vibration mitigation.

Ground-Borne Train-Induced Vibration

Along with the coal mining industry in Scranton came the railroad business that transported coal to ports in larger cities for eventual distribution around the country. While the last mine in Scranton closed down in the mid 1960s, the railroad track that lies less than 100 feet from the new Loyola Science Center is still in use. Today it transports not coal but tourists from the nearby Steamtown National Historic Site, as well as carloads of goods transported throughout the Delaware-Lackawanna Line. These historic steam trains and freight trains were potential sources of ground-borne vibration disturbances to the new science building. There is yet no generally accepted, comprehensive model for predicting train-induced structural vibrations inside a building. Structural engineers must therefore rely on partially empirical techniques for predicting the transmission and propagation of vibration from a railroad traffic source as it enters into the building base or foundation, as it proliferates through the building structure, and as it is finally transmitted into the receivers (i.e. vibration-sensitive equipments and occupants).

Normally, the level of vibration in the foundations is lower than that in the surrounding ground due to the foundation coupling loss that occurs as vibration is transmitted from the ground into a building. For mat slab bearing on bedrock, the coupling loss may only be very minor or nil. Since concrete is just as dense as rock, the concrete and bedrock therefore have the same mechanical impedance properties (no material mismatch). The foundation design for the new LSC therefore ensures that the mat slab bears on a different intermediate soil media and not directly on the bedrock, since the separation created by the layer of structural fill materials between the mat slab and the bedrock produces impedance mismatch and would result in foundation coupling loss. The physical size and mass of the building, and the characteristics of its foundation, also contribute to the level of attenuation of ground-borne vibration inside a building.

A mid-value of -6 VdB coupling loss was assumed in the prediction process for the LSC Project. Vibration can be expressed in linear (μ in/sec) or logarithmic amplitude scales. Ground-borne vibration is normally expressed in a logarithmic scale VdB (vibration velocity level in decibel). In this scaling, any increase in level of 6 VdB represents a doubling of amplitude regardless of the initial level. Therefore, the aforementioned value -6 VdB due to assumed coupling loss basically implies that ground-borne vibration is reduced by half as it enters into the foundation of the new LSC. Vibration amplification due to

Mat Slab Foundation Construction.

excitation by the floor's own natural frequency was also considered in the predictions and assumed to be +12 VdB. In like manner, this change represents an amplification factor of 4. Losses also occur with the transfer of vibration from floor to floor due to structural damping and geometrical spreading. In the predictions, -2 VdB floor-to-floor attenuation was assumed. All in all, a net change in ground-borne vibration level of +4 VdB was assumed in the predictions due to foundation coupling loss, resonance of floors, and floor-to-floor attenuations. Pre-construction measurements of on-site ground-borne vibrations were taken over an approximately 24-hour period in two spots, at both ground level and bedrock, that border vibration-sensitive areas in the building. As expected, vibrations nearer to railroad traffic were higher than those farther away, since ground naturally attenuates vibration as it moves further away from the source. The maximum measured train-induced vibrations on the bedrock were 1,050 μ in/s (65.4 VdB) and 460 μ in/s (58.3 VdB) at the nearest and farthest locations respectively. With the predicted net change in vibration level of +4VdB, the anticipated most severe train-induced vibrations at the above-grade floors would be 69.4 VdB, equivalent to approximately 1660 μ in/s. At the ground level, the measured vibrations were 1,500 μ in/s at the nearest location and 500 μ in/s at the farthest location. These would be the expected trained-induced vibrations at the underside of the slab on grade for buildings with conventional foundations. In the mat slab-supported LSC, whose mat slab foundation encompasses the entire building footprint, ground-borne vibration transmission into the ground-floor slabs are minimized, making the ground floor ideal for program spaces with highly sensitive equipments or occupants.

Conclusion

The use of a mat slab foundation system mitigates the risk of the structural failure of the new LSC due to potential ground subsidence. Project structural engineers predicted that mat slab bearing on a different intermediate soil media that separated the foundation from bedrock could result in foundation coupling loss and improve the vertical vibration mitigation. Observed train-induced vibration levels inside the completed building support predictions and confirmed compliance to the design goal: moderately sensitive equipments, such as microscopes at magnifications up to 400X and analytical balances, can generally be used without disturbance within the laboratory spaces of the new Loyola Science Center. The laboratory spaces in the building can also accommodate highly sensitive equipment in vibration isolation systems.▪

Alvin P. Tabar, P.E. is a Senior Associate with EYP Architecture & Engineering, structural engineers for this project. He can be reached at ***atabar@eypae.com****.*