U.S. Department
of Transportation
Federal Highway Administration

Office of the Administrator

1200 New Jersey Ave., SE
Washington, D.C. 20590

December 13, 2011

In Reply Refer To:
HIBT

The Honorable Stephen F. Lynch
U.S. House of Representatives
Washington, DC 20515-2109

Dear Congressman Lynch:

Thank you again for your letter regarding a soil depression detected along the Amtrak line adjacent to the I-90 Connector Tunnels. To determine whether the depression might affect motorist safety, I appointed an assessment team of experts in geotechnical and structural engineering to conduct an independent structural assessment.

The team found that the tunnels are not showing any signs of excessive stress or other indications that might suggest structural damage or progression towards reduced motorist safety or performance. The engineers that designed the tunnels anticipated some settlement, which is a natural result of the thawing of soil that had been frozen during the construction period. I have enclosed a copy of the assessment team's report.

The team based its conclusions on discussions with the Massachusetts Department of Transportation (MassDOT), the Massachusetts Bay Transportation Authority, the Federal Railroad Administration, and Amtrak. In addition, the team participated in site visits and project meetings, examined project documents, and reviewed monitoring results to assess the soil problems, the remedial actions taken, and the impact on the tunnels.

As mentioned in my August 25 letter, officials have been inspecting the I-90 Connector Tunnels since they opened to ensure they remain in alignment for safe use. These inspections will continue to measure any further changes that might in any way affect the structural integrity of the tunnels. The team will continue to review information from the site.

If I can provide further information or assistance, please feel free to call me.

Sincerely,

Victor M. Mendez
Administrator

Enclosure

Structural Assessment of I-90 Connector Tunnels at South Station Boston, Massachusetts

FEDERAL HIGHWAY ADMINISTRATION

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EXECUTIVE SUMMARY

At the request of Congressman Stephen F. Lynch, the Federal Highway Administration (FHWA) formed an independent team to assess the I-90 Connector Tunnels in Boston, Massachusetts. The team worked with the Massachusetts Department of Transportation (MassDOT), Federal Railroad Administration (FRA), and Amtrak to understand the ground settlement adjacent to the tunnels and railroad tracks and assess potential structural impacts. The assessment included review of existing documentation on construction of the tunnels, post-construction monitoring results, and plans for further remedial actions. The team met with MassDOT, FRA, and Amtrak representatives and visited the site.

Based on this review, the team concluded that the large amount of settlement is due to thawing of soil that was frozen to a depth of 130 to 140 feet during construction. This deep freezing was done only in a small area and it is likely that the extent of the large settlement is similarly constrained. This interpretation is consistent with observations at the surface.

The team could not discern whether a void, which has been inaccurately referred to as a "sinkhole," exists and was caused by the settlement below a portion of the tunnels where deep ground freezing occurred. However, the tunnel design is such that even if a void did form, it would not impact the safety or performance of the tunnels without first experiencing a prior period of observable distress. The ongoing inspection of the tunnels has not shown this type of distress. The current course of action appears reasonable and prudent. It involves further investigation, monitoring, observation, and planning to address the ground settlement as the thawing comes to an end.

Structural Assessment of I-90 Connector Tunnels
at South Station
Boston, Massachusetts

BACKGROUND

The Central Artery/Tunnel Project was one of the most complex engineering projects ever undertaken and featured several first-time, innovative, or largest-ever engineering applications. Ground freezing for excavation support during construction of the connector tunnels is one good example.

The I-90 Connector Tunnels run from I-93 near South Station beneath railroad tracks, the Fort Point Channel, and South Boston before connecting to the Ted Williams Tunnel on the way to Boston Logan International Airport. To construct this section of I-90 without impacting Amtrak and Massachusetts Bay Transportation Authority (MBTA) operations, ground freezing was used to stabilize the soil beneath the railroad tracks as that portion of the connector tunnels was jacked into place. For the duration of construction, soil within the tunnel footprint was frozen to depths of approximately 50 to 60 feet, which corresponds to the lowest elevation of the tunnel sections. As the tunnel sections were advanced from west to east through the frozen soil and beneath the railroad tracks, circulation pipes used for this shallow freezing were removed and thawing began immediately.

Driven by the sequence of construction for the tunnel contracts, a deep temporary excavation support system was also designed using ground freezing at the eastern edge of the jacked tunnel sections. Deep freezing for this work extended to depths of approximately 130 to 140 feet below the ground surface across the eastbound I-90 tunnel and extending away from the railroad tracks between the eastbound and westbound tunnels into the current United States Postal Service (USPS) property. Deep freezing in this area was maintained until 2002; well after tunnel jacking was complete.

In 2002, the freeze plant was shut down and the deep frozen soil mass began the slow process of thawing. While some ground settlement was expected in the area of deep freezing, the thawing of the frozen soil during the past 9 years has resulted in greater settlement than expected. The Massachusetts Department of Transportation (MassDOT), Amtrak, and MBTA began monitoring the magnitude and rate of this settlement in 2003. Settlement has been observed and documented in the following locations:

- USPS parking lot near the Central Artery Tunnel Ventilation Building Number 1;
- Below the two eastern most railroad tracks (Track Nos. 14 and 16);
- Amtrak catenary support foundation No. 157A;
- An MBTA electrical duct bank;
- A 42-inch storm drain line; and
- A 12-inch water line.

The large settlement appears to be related to the limits of the deep ground freezing between the eastbound and westbound tunnels. The ongoing settlement has totaled approximately 8 feet to date. Because some deep ground freezing of soil occurred under the I-90 eastbound tunnel, the possibility exists that a void has formed beneath the structure. This has led to speculation by some that the I-90 tunnel is in danger of failure.

In August 2011, at the request of Congressman Stephen F. Lynch, the Federal Highway Administration (FHWA) assembled a team of experts in geotechnical and structural engineering to conduct an independent structural assessment. Through site visits and project meetings, examination of project documents, and review of monitoring results, the team found that the tunnel has not shown any signs of excessive stress or exhibited other indications that might suggest structural damage or progression towards reduced performance or failure. Monitoring will continue to measure any further changes that might in any way affect the structural integrity of the tunnels.

FHWA ASSESSMENT ACTIVITIES

The FHWA Assessment Team's objectives were to:

- Meet with MassDOT and its consultants to gain a better understanding of their observations and the construction history;
- Review available documentation on design assumptions and calculations for the ground freezing and tunnel jacking operations, the adjacent cut and cover tunnel operation, and current instrumentation and monitoring efforts on the structures and surface settlement;
- Provide an independent assessment of the actions being taken by MassDOT at this time; and
- Assess the structural condition of the I-90 Connector Tunnels.

The FHWA undertook the following activities:

- Representatives of FHWA's Office of Bridge Technology and Massachusetts Division Office met with the Federal Railroad Administration (FRA), Amtrak, and MBTA on August 18, 2011. This was an information meeting to discuss the proposed remediation strategies for removal and replacement of a thick ballast pocket under railroad tracks affected by the freeze-thaw settlement.

- The FHWA Assessment Team and Massachusetts Division Office met with MassDOT and CA/T consultants (STV Parsons and GZA Consultants, Inc.) on August 23, 2011. The scope of this initial meeting with MassDOT was to:

    - Obtain an overview of the settlement and the potential impact on the I-90 Connector Tunnels from those who have been monitoring the site;

- Discuss the ground freezing beneath the railroad tracks and better understand subsurface conditions, predicted versus actual settlements during thawing, and any anticipated impacts on structural performance;
- Obtain information on any remedial actions that have been completed by MassDOT during soil thawing to repair damage or control or monitor settlement;
- Obtain information on any remedial actions to repair damage, or control or monitor settlement that are ongoing as a result of soil thawing;
- Obtain information on any plans to further investigate or mitigate current issues related to the thawing soil; and
- Visit the site to observe the scope of the settlement problem and site constraints.

During the meeting, FHWA requested copies of any relevant documentation on design assumptions and calculations for the ground freezing and tunnel jacking operations; construction and inspection reports for the ground freezing and tunnel jacking operations; and current instrumentation and monitoring efforts on the structures and surface settlement.

The FHWA Assessment Team reviewed the following:

- Copies from the archives of the Central Artery/Tunnel construction files provided by STV Parsons. Documents from 10 archive boxes provided information on:

  - Design assumptions for the ground freezing to stabilize the railroad tracks;
  - Deep ground freezing for support of excavation adjacent to the railroad tracks;
  - Drilled shafts installed for ground improvement and support of the adjacent cut and cover tunnel section; and
  - Incident reports for remediation of obstructions and voids encountered during tunnel jacking operations below the railroad tracks.

- STV Parsons' structural report dated May 12, 2011, summarizing the results of finite element numerical models of the I-90 eastbound jacked tunnel. The models were created to perform a theoretical evaluation of the tunnels assuming a hypothetical void below the structure.
- Geophysical survey prepared by Hager GeoScience, Inc., dated November 2009, summarizing non-destructive testing conducted through the floor of the I-90 eastbound tunnel. The purpose of the investigation was to determine the feasibility of using geophysical methods to identify potential voids beneath the structure.
- Phase II Geotechnical Engineering Report by GZA GeoEnvironmental, Inc., that assesses the ongoing ground settlement in the area between the two I-90 tunnels and adjacent to the railroad tracks. In addition to analyzing the anticipated magnitude and duration of remaining settlement, the report recommends measures for potential remediation.

- Minutes prepared by STV Parsons for regular stakeholder meetings to discuss the ongoing ground settlement monitoring program, drainage pipe integrity, and Amtrak repairs. Included with the minutes are geotechnical instrumentation data summary reports for monitoring programs started in September 2009 to study the post-construction ground settlement and potential structural impacts.
- Amtrak Contract Documents for South Station Tower I ballast pocket removal below Tracks 16 and 14. The plans describe and specify interim repairs to remove and replace approximately 8 feet of ballast placed below the railroad tracks to accommodate ground settlement since 2003.
- A proposed scope of work to conduct additional subsurface explorations and testing, install new instruments, monitor new and existing instruments, undertake periodic tunnel inspections, and continue meeting regularly with stakeholders.
- Several literature references, including journal articles and conference papers, discussing design and construction considerations for the ground freezing, tunnel jacking, and related ground improvement activities conducted in the area of South Station and Fort Point Channel.

- The FHWA Assessment Team observed the ballast pocket removal work in October 2011 as part of the Amtrak track repair project to confirm the depth of the ballast pocket and assess the quality of the ballast in place.

DISCUSSION OF FINDINGS

Site Conditions

The area occupied by the railroad tracks and immediately east toward the Fort Point Channel is a reclaimed fill site with very poor soils existing within the majority of the footprint of the tunnel structures. The soil profile in this area consists of heterogeneous fill materials to a depth of approximately 50 feet. These materials are loose to very dense sands and gravels with debris consisting of previously abandoned building foundations, masonry sewer pipes, granite seawalls, and timber piles and pier remnants. Below the fill deposits is a relatively thin layer of organic silt and clay. This layer was not encountered everywhere on the site and was less than 5 feet thick where it was encountered.

Marine clays underlie the organic silt at this site to a depth of approximately 120 to 130 feet. The stratum is normally consolidated through most of its depth, with a stiffer (overconsolidated) upper section that is 10 to 15 feet thick. Below the marine clay is glacial till.

Ground Freezing

To successfully advance the tunnel sections, the highly variable and weak soils within the tunnel footprint required stabilization. Ground freezing was chosen to stabilize these soils because it

limited the potential for ground movement and loss of ground, and provided support at the front face of the tunnel to facilitate excavation and removal of material.

Ground freezing was completed by installing a closed system of steel pipes in the soil and circulating a brine solution. As the temperature of the soil is decreased, the water in the soil freezes. The soil freezing begins near the pipes and advances in all directions. Because the volume of ice is approximately 9 percent higher than the volume of water, volume change in the soil was expected. The amount of volume change is dependent on a number of factors, with the soil type being one of the most important. The amount of volume change in sand and gravels is not expected to be high because the permeability of the soil is high and water can flow away from the freezing front. However, in low permeability soils such as marine clay, volume change can be significant.

Some low permeability soils are able to draw in additional water as they freeze and expand, sometimes creating lenses of pure ice. In general, when soil expands, or an ice lens thickens, it will do so in the direction of least resistance. Near the ground surface this is likely vertical, and can be observed as surface heave. Where deep ground freezing occurred in the normally or lightly overconsolidated soils, the direction of freezing was more likely to be horizontal. In fact, samples recovered from drill holes contained vertical ice lenses in ground that was still frozen.

Ground freezing along the I-90 Connector Tunnel footprints extended laterally approximately 15 feet beyond the structure sides and to a depth of approximately 50 to 60 feet below the ground surface. This depth of freezing was just above the bottom of the tunnel structure. At the eastern edge of the Amtrak property, a second, deep ground freezing operation was completed to facilitate connection of the jacked tunnel section to the adjacent section constructed by a more traditional cut and cover technique. The deep ground freezing extended an additional 70 feet below the shallow freezing in an area within the eastern edge of the footprint of the eastbound I-90 tunnel and extending away from the railroad tracks into the USPS property between the eastbound and westbound tunnels. As the tunnel was advanced, shallow freeze pipes used for soil stabilization were removed and soil thaw began. Where deep freezing was occurring, freeze pipes were maintained until long after the tunnel jacking operation was complete to provide support for the adjacent open excavation.

Deep ground freeze pipes installed for excavation support were designed as a series of rectangular foundation barrettes to ensure stability and safety during construction. As the freezing front advanced, the barrettes formed a series of cylindrical to rectangular shaped areas that were much deeper than they were wide. This formation further emphasized the importance of lateral movement in accommodating the volume expansion from freezing. Additionally, soil that expands laterally during freezing will not return to its original position upon thawing; it will be impacted by the force of gravity and the compressibility and shear strength of the thawing material, and will likely result in settlement amounts that exceed initial heave when the balance of forces and strengths come together in time.

While the magnitude of settlement may be surprising, its occurrence is not, and estimation of the amount of settlement at this location is complex and difficult. Documents reviewed did have

heave and settlement calculations but they were not sophisticated enough to capture the irregular three-dimensional geometry of the frozen ground and the advance and retreat of vertical freezing fronts in the deep freeze area, or changes to soil strength and compressibility as a result of freezing.

Construction

The reinforced boxes for the jacked tunnel sections were cast in the jacking pit prior to being jacked into the frozen soil. The walls of the boxes were very thick – approximately 8 feet thick on the top and bottom and 7 feet thick on the sides – and a steel cutting edge was added to the front of the box to aid in the excavation of material from within the boxes. A roadheader, which is essentially a rotating claw, was used to excavate the frozen material from the face of the tunnel except where obstructions were encountered. Obstructions, including granite, concrete, masonry, and timber were frequently encountered and were excavated using the best means available.

Anti-drag devices were used on the sides and top of the tunnel to reduce any friction between the tunnel sections and the surrounding soil material. Grease ports, which were also used to reduce friction, were eventually used to inject grout and fill voids adjacent to the walls and top of the tunnel. In the area of deep ground freezing, obstructions were encountered, and the excavation was oversized slightly to reduce the potential for drag forces to cause failure of the excavation face as the tunnel box was pushed to the opening. The obstructions, overexcavation, and the potential for a variably frozen condition of the ground suggest that the contact between the tunnel and the ground may be quite variable.

The contract for construction of the cut and cover tunnel to the east of the jacked section required stabilization and strengthening of the soils below the tunnel invert. Deep soil mixing using cement was done throughout the area and was carried as close as practical to the jacked tunnel sections. Due to known subsurface obstructions and the sequence of contracts, deep soil mixing was not practical to support the headwall of the jacked sections or the invert near one area just east of the northern part of the eastern terminus of the eastbound tunnel. Through design changes, a group of deep drilled shafts was installed for stabilizing soft ground adjacent to the deep ground freezing barrettes and to provide support for the tunnel. It is not known if there is a link between the shafts, the performance of the deep ground freezing, and the observed settlement and tunnel performance, but the fact that the areas are immediately adjacent to each other is noteworthy.

Monitoring

Monitoring has been ongoing at the site since 2003. Measurements are being recorded monthly from:

- Amtrak Catenary Support Foundation No. 157A: The foundation for one of the catenary poles serving Amtrak began to settle significantly once the freeze plant was shut down in 2002. Unable to keep up with the rate and magnitude of settlement, Amtrak took the pole

out of service. Beginning in May 2003, MBTA and Amtrak monitored settlement of the catenary support foundation using four survey points located on top of the element.

- 42-inch Storm Drain Pipe Instruments: A 42-inch pipe encased in a 60-inch steel shell was installed approximately 50 feet below the surface between the eastbound and westbound tunnels. The pipe runs parallel to the tunnels and the annular space between the steel and concrete sections was filled with cement grout. During inspection and repair of damage from settlement in November 2009 to utilities in the thawing soil, the following instrumentation was installed:

    - A Shape Acceleration Array – Field (SAAF) was installed at the upper crown of the 42-inch pipe over the length of the deformed section. The SAAF provides a settlement profile over the length of the pipe where installed.
    - A vibrating wire crack meter was installed in the pipe to monitor the change in width of one of several cracks inside the pipe. This is an indicator of ground movement and pipe deformation.

- Borehole Instruments: During the summer of 2008, drill holes were completed to investigate still frozen and thawing soils in the area of deep ground freezing. Specifically, the following instruments were installed in three of the drill holes:

    - Vibrating wire piezometers with thermisters were installed to record subsurface temperatures and water pressure in the soil.
    - Inclinometers were installed to measure lateral movement of the soil at depth.
    - Multiple Point Borehole Extensometers were installed to record the soil settlement with time at different intervals of depth below ground surface.

Observed Settlement

Survey data from the catenary support foundation and observation of the depth of ballast pocket removal indicate that at least 8 feet of settlement occurred in the localized area bounded by the I-90 eastbound and westbound connector tunnels, tracks 16 and 14 on the Amtrak property, and the area between the MBTA utility line and the pump station on the USPS property. The area corresponds with the location of deep ground freezing activities that affected soils to a depth of approximately 130 to 140 feet. Based on review of the available information, and observations made during three site visits, the area of deep ground freezing is the only area that appears to be undergoing settlement of this magnitude.

While deep freezing occurred under a portion of the eastern edge of the I-90 eastbound tunnel, settlement has not been observed and a void has not been confirmed. Geophysical surveys by Hager GeoScience, Inc., indicated that anomalies may exist below the floor of the I-90 eastbound tunnel, meaning that the physical response of the ground varies under different portions of the tunnel. The methods used by Hager GeoScience are experimental and the company's own conclusion is that more should be done to confirm its findings. One alternative explanation of the potentially different conditions below the tunnel is that where obstructions were present, as

reflected in the construction log, an overexcavation was performed to reduce drag in the area where a settlement-induced void could be anticipated.

Based on several geotechnical monitoring instruments installed in 2008, instrumentation installed inside the 42-inch drain pipe, and other monitoring points, the total rate of soil settlement has been consistent for several years at approximately 1 inch per month. Recent data provided by GZA GeoEnvironmental indicates that the rate of settlement is beginning to slow however; the Assessment Team believes that it is too early to draw a definitive conclusion on this trend.

Monitoring data indicate that as the thaw front progresses, increased activity occurs in the instruments (significant lateral and vertical deformation), followed by a leveling off of movement. Pore pressure measurements also indicate little to no excess pore water pressure in the soil during thawing. This may mean that the structure of the clay has been disturbed and soil settlement is complex. As noted earlier, documents reviewed did have heave and settlement calculations, but none sophisticated enough to capture the irregular three-dimensional geometry of the frozen ground and the advance and retreat of vertical freezing fronts in the deep freeze area, or changes to soil strength and compressibility as a result of freezing.

Subsurface exploration data and monitored temperature instruments indicate that an approximately 10 to 15 foot thickness of frozen soil remains from the deep freezing activities at a depth of approximately 90 to 110 feet below the ground surface. This is not a large volume considering how much soil was frozen, and it supports the finding that the rate of settlement may be slowing.

Based on our understanding of the freeze process, soil freezing and subsequent thawing occurred in a complex manner. Shallow freezing occurred prior to deep freezing, and the deep freezing was designed in barrettes that likely froze and expanded radially from the freeze pipes. Vertical ice lenses observed during subsurface explorations support this. While the depth of soil thaw is being measured, a significant amount of the deformation observed at the site may be due to volume change occurring in three dimensions.

STRUCTURAL ASSESSMENT

At the time of this report, regular inspections of the inside of the I-90 tunnels are being performed at a frequency that is normal for tunnel maintenance. These inspections have not detected any evidence of excessive stress in the reinforced concrete tunnel structures or indicated that structure damage has occurred. The STV Parsons theoretical evaluation suggests that if the tunnel had to span a large void, it could do so safely. This evaluation is preliminary and believed to be conservative because it is based on a simplified representation of the tunnel and intended to represent a "worst-case" scenario.

CONCLUSIONS

The observed settlement adjacent to the I-90 connector tunnels appears to be localized and specifically related to the deep ground freeze-thaw activity. Because some deep freezing of soil occurred in areas within the footprint of the I-90 eastbound tunnel, observed settlement indicates the potential for a void beneath the structure. This is only a presumption, however, as there has been no confirmation of a void.

Simplified and conservative analysis shows that the tunnel could span a large void if it did exist or were to form. The tunnel has not shown any signs of excessive stress nor exhibited other indications that might suggest structural damage or progression towards unacceptable loading, reduced performance, or failure. Regular inspection is ongoing and this is a reasonable and prudent approach at this time.

The FHWA Assessment Team is continuing to review information on the project and is monitoring on-going work being conducted by MassDOT's consultants. As of this report, work is underway on the scope of additional work proposed by STV Parsons and GZA GeoEnvironmental, Inc. The FHWA Assessment Team intends to review information from this work to re-evaluate initial findings.

RECOMMENDATIONS FOR ADDITIONAL WORK

Based on review of the information provided, the soil in the area of the I-90 connector tunnels will continue to thaw and settle. Estimates provided by GZA GeoEnvironmental indicate that this settlement may continue until as late as 2014.

The FHWA Assessment Team has reviewed the general scope of work being executed by STV Parsons and GZA GeoEnvironmental. While we were unable to review a more detailed scope that provided specific information on proposed work, we believe that the proper course of action is being taken to protect public safety and ensure the integrity of the tunnel. Regarding any future work to inspect the tunnel boxes, or to attempt to identify and characterize any potential void beneath the tunnel, FHWA has the following comments:

1. The tunnel inspection frequencies are predetermined through 2014. The Assessment Team understands that this timeline is for cost estimate purposes, and the contract will allow for flexibility in monitoring to deal with possible changes in performance. Reading thresholds should be set that would allow the consultants to accommodate any increase or decrease in inspection frequency.

2. Instrumentation and monitoring of the I-90 westbound tunnel should be considered. The eastbound tunnel is considered more critical given the geometry of the deep freezing, but the location of surface settlement suggests that the performance of the westbound tunnel should be monitored along with the eastbound.

3. An optional scope item has been proposed for follow-up geophysics below the eastbound tunnel to help identify the extent of any voids that may be present. If MassDOT advances this task, the project should also consider more rigorous analysis methods for using existing data in combination with three-dimensional techniques (e.g., tomography) to better visualize and characterize any anomalies that may be discovered.