decay of the buried timber, and periods of higher antecedent precipitation.

An efficient and low cost means of investigating and mitigating these hazards is needed. This paper discusses CP’s experience over the past three years. The investigation of these sites need to focus on non-destructive methods capable of covering the linear geometry of the the railway corridor. Geophysical methods, including GPR and other seismic techniques with the resolution to identify the voids despite the presents of other solids within the embankment appear to provide the best option.

Mitigation methods need to focus on subsurface treatment that can be completed with minimum of disturbance to the surface and near surface rail bed and require limited access to the track. Several options have been identified and used with varying levels of success.

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REFERENCES

150 mm and a length of about 5 to 6 m. The lateral capacity of the columns was further increased by the use of hollow steel drill stem and bits, which were left in place within the column to form integral reinforcement.

Zones where DBT had been identified were treated with an array of 20 soil columns arranged into an interlocking A-frame array over the buried timber trestle. The columns were positioned so that they could be easily inserted between tie locations. The inter column distance within the array was maintained at less than 0.3 m to create a reinforced soil mass and reduce the potential for large sinkholes to migrate upwards through the soil treatment zone.

Typical equipment set-up is shown in Figure 5. The placement of each group of soil cement columns was set at known DBT locations. Timber-remnants and voids were encountered during installation, and monitoring of total grout volumes, void fill volume and column volumes were tracked. The volume of grout consumed in filling of voids was in the same order of magnitude as typical timber volumes (8 m$^3$), giving some confidence that future void collapse and subsequent sinkhole formation was prevented.

5.1.5 Deep Vibration Treatment

Deep vibration treatment – was attempted in a limited, trial basis at BELL195.12 to compact the fill and collapse voids at depth. A vibratory pile driver, fitted with a probe fabricated from heavy plate and an H-pile section were driven at the known locations of a limited number of DBT bent locations on the east approach to a short bridge. Accelerometers were placed in order to determine the relative effects of the deep vibration on the adjacent structure. Track structure profile was monitored prior to, and for a period of about 2 months following the test in late 2005.

Figure 5. Installation of Soil-Cement Column

Pre and post-treatment monitoring showed that the track structure settled in a predictable manner over a period of 6 weeks after treatment. Field observation indicated that there did not appear to be much energy delivered to the subgrade beyond a distance of about ½ meter from the centre of the vibratory probe. While easily implemented with conventional railway construction equipment, further development would be required.

5.1.6 Further Characterization of Trestle Condition

It would be desirable to have a non-intrusive method to assess the likelihood of sinkhole formation where extensive lengths of DBT are suspected. Several remote sensing investigation methods were tested to locate and assess the condition of buried trestles. GPR and Surface wave techniques require further development to meet reliability requirements.

7. CONCLUSIONS

Several railways in North America have encountered DBT in the embankments where the track was once supported by a timber trestle. As railway infrastructure ages more DBT sites will be identified and require mitigation. The actual formation of the sink holes appears to be related to the soil conditions, age and state of
5.1.1 Void Filling from the Surface

This option has been utilized in numerous location by CP and other railways where there limited understanding of the nature or cause of the sinkhole. It commonly includes shallow excavation of the sink hole to 1 to 2 meters below the base of rail and backfilling with compacted soil. This is common practice where track maintenance personnel have no knowledge of a potentially systemic DBT condition.

5.1.2 Placement of Geosynthetic

This option for treatment of potential sinkholes has been utilized by others in areas with sinkholes related to Karst or buried anthropogenic features such as ditches or pits as described in Villard et al. (2000). This method requires removal or deactivation of the track structure while the upper 2 to 4 m of embankment is subexcavated and replaced with geosynthetic reinforcement and compacted backfill material. This method provides an engineered tensile element which reduces the magnitude and localization of potential sinkholes. Excavation, disruption to railway operations, and difficult access for heavy earth-moving equipment are constraints that make it difficult to implement. Limitations on the time available to complete the work due to train schedule requirements often results in less than adequate compaction. As a result, this method typically introduces a track settlement condition in the vicinity of the excavation that may last for several months and require additional track maintenance.

5.1.3 Void Filling and Slurry Grouting

Slurry grouting and void filling methods utilize drilling and grouting equipment to introduce cement/sand or urethane grout at depth within the embankment. The grout is injected through drilling equipment and the grout consistency and injection pressure are varied to fill voids or compact adjacent soil. The advantages for this treatment method are it can be targeted at deep potential sinkhole forming zones, the equipment can be operated off-track to minimize railway disruptions. The disadvantages of this method are it requires preliminary site investigation to identify localized treatment zones targets, it requires specialized equipment and personnel, is costly and does not treat for future sinkholes that may form with continuing timber decay.

Slurry grouting was carried out as an initial response at several sites, to remove the immediate risk posed by the presence of voids associated with visible sinkhole formation. Where conditions permitted, the slurry grouting was followed by construction of soil-cement columns. The slurry grouting method uses similar equipment to that used in construction of soil-cement column bents, but requires less drilling and much less time per bent than for soil-cement column installation. In many cases the grouting operations were carried out concurrently with geotechnical investigations to shorten schedules and minimize disruption of railway operations.

5.1.4 Soil-Cement Columns

Soil-cement column bents were constructed at MACT028.02, BELL194.6, and MACT057.6. Where sinkhole formation was active, the array of soil cement columns was combined with an initial stage of void fill grouting to further improve conditions within the embankment.

The method utilized an array of reinforced soil-cement columns above the zone of potential sinkhole formation, using drilling equipment and controlled velocity fluid/grout circulation to create a soil/cement column within the ground. The column diameter and strength are controlled by the injection velocity and cement content of the grout. The equipment and methods employed at the railway embankment sites resulted in a nominal column diameter of
There is some indication that high antecedent rainfall is a trigger to DBT collapse possibly through formation of an infiltrating wetting front reducing capillary tension allowing the collapse of “arched” voids. A time lag between precipitation events and appearance of sinkholes was observed. Additional investigation is needed. The presence of more localized high-intensity events, and high antecedent soil moisture conditions trigger sinkholes during “wet” periods. Antecedent rainfall conditions are shown in Figure 4.

![Figure 4. 2005/2006 daily and 21-day antecedent rainfall at Toronto-Pearson Int. Airport.](image)

5 ENGINEERING TREATMENT

Based on the hazard associated with sinkhole formation, several options were considered for mitigating locations where the hazard had been identified.

5.1 Ground Treatment Options

Treatment options were selected based on the operational constraints and site requirements. The options considered included:

- Void filling with soil from the surface
- Excavation of the shallow subgrade and replacement with a geosynthetic reinforced soil
- Subsurface void filling and compaction grouting
- Installation of soil-cement columns
- Vibratory compaction
- Further characterization (improved assessment of risk—geophysical methods) to increase the information about the size and distribution of the voids and related hazards

Numerous factors such as ease of implementation, access, hazard reduction, equipment availability and cost, were considered in determining the preferred solution where sinkholes and decayed buried timber trestle have been identified. A description and comparison of limitations for each option are described below:
occurring. A perceived hazard therefore exists where old timber trestles are buried within embankments because of the location and volume of buried timber, and the lack of indication of potential void formation or impending sinkholes beneath the track.

The extent of abandoned trestle structures at any given location is usually greater than 30 meters, and at each 5 meters along the track 8 cubic meters of DBT are present (for an average 10 meter depth of fill). The potential loss of roadbed and ballast, concentrated at a single location could lead to significant changes in track geometry. The condition of trackage is monitored on a daily basis, formally inspected about 3 times per week and there is no clear evidence that visual inspection, or automated quarterly track geometry inspections can detect the potential formation or sinkholes, or the precursors to sudden loss of roadbed support for the track structure. Table 3 summarizes these hazard indicators for each location.

Table 3. Risk factors/indicators

<table>
<thead>
<tr>
<th>Indicators</th>
<th>MACT028.02</th>
<th>BELL194.6</th>
<th>BELL195.12</th>
<th>MACT057.6</th>
<th>BELL181.48</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automated Track Geometry Report date</td>
<td>2004/10/19</td>
<td>2005/08/03</td>
<td>2005/08/03</td>
<td>2006/02/20</td>
<td>2006/06/27</td>
</tr>
<tr>
<td>Antecedent Rainfall Accumulation:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 day</td>
<td>52.2 mm</td>
<td>86.6 mm</td>
<td>64.4 mm</td>
<td>83.4 mm</td>
<td>56.4 mm</td>
</tr>
<tr>
<td>24 hour</td>
<td>16.4 mm</td>
<td>41.4 mm</td>
<td>22.0 mm</td>
<td>35.2 mm</td>
<td>12.6 mm</td>
</tr>
<tr>
<td>Sinkhole formation</td>
<td>Conical depression</td>
<td>Conical depression</td>
<td>Conical depression</td>
<td>Conical depression</td>
<td></td>
</tr>
<tr>
<td>0.4 m wide, 2 m deep east of bridge</td>
<td>0.5 m wide</td>
<td>0.2 m deep</td>
<td>1.5 m deep</td>
<td>0.5 m wide</td>
<td></td>
</tr>
<tr>
<td>0.2 m deep, east of bridge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.2.1 Track Geometry

Track geometry measurements are automated. Specially equipped Track Evaluation Cars (TEC) on most large North American Railways generate defect reports indicating rates of change in alignment are output so that locations exceeding prescribed thresholds may be monitored and corrected. As summarized in Table 3 review of TEC reports did not indicate any clear trend in defect type or magnitude that could act as a warning of impending sinkhole formation.

4.2.2 Precipitation/Infiltration
<table>
<thead>
<tr>
<th>Site:</th>
<th>MACT028.02</th>
<th>MACT057.6</th>
<th>BELL181.48</th>
<th>BELL194.6</th>
<th>BELL 195.12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>North of Bolton, ON, crossing of Humber River</td>
<td>Barrie, ON, crossing of Bear Creek/Utopia Reservoir</td>
<td>Whitby, ON, crossing of Lakeridge Rd.</td>
<td>East end of Toronto, ON, crossing of Rouge River</td>
<td>East end of Toronto, ON,</td>
</tr>
<tr>
<td>Site Elevation</td>
<td>256 m</td>
<td>211 m</td>
<td>106 m.</td>
<td>152 m</td>
<td>157 m</td>
</tr>
<tr>
<td>Surflcial Geology</td>
<td>Halton Till near south edge of Oakridges Moraine</td>
<td>Simcoe Lowlands, Camp Borden Sand Plain.</td>
<td>Lake Iroquois Plain, South of South Slope</td>
<td>Newmarket Till, near South Slope of Lake Iroquois Shore. Incised River Valley</td>
<td>Newmarket Till, near South Slope of Lake Iroquois Shore.</td>
</tr>
<tr>
<td>Height of fill</td>
<td>25 m</td>
<td>10 m</td>
<td>7 m</td>
<td>16 m</td>
<td>8 m</td>
</tr>
<tr>
<td>Length of site</td>
<td>192 meters, centered on stream crossing location.</td>
<td>82 meters, centered on culvert stream crossing</td>
<td>450 meters, centered on roadway crossing</td>
<td>110 meters, on East approach to bridge.</td>
<td>10 meters, on East approach to bridge</td>
</tr>
<tr>
<td>Year of trestle construction</td>
<td>1909</td>
<td>1908</td>
<td>1911</td>
<td>1910</td>
<td>1910</td>
</tr>
<tr>
<td>Year of replacement structure construction</td>
<td>1910 Double 4.3 m arch culverts</td>
<td>1913 - Single 6 m arch culvert</td>
<td>1913 - Single 3 m culvert 1980 - grade separation</td>
<td>1912 to 15 5 span steel bridge 1929 abutments</td>
<td>1912</td>
</tr>
</tbody>
</table>

The depth of sinkholes measured by hand probing with a steel bar ranged from 0.6 to greater than 3 m. In one case hand probing of a void encountered during test pit excavation extended to a depth of 11 m below track level with no significant resistance. The appearance of sinkholes appears to be correlated with infiltration occurring after high intensity precipitation events. However, the effect of rainfall must be understood to be a combination of antecedent conditions, high-intensity events preceding sinkhole formation and the geotechnical conditions within the embankment.

4.2 Hazard Assessment

The formation of sinkholes in the top of embankments which supports the rail structures increases the likelihood of track defects.
Table 1 Summary of Geotechnical Properties

<table>
<thead>
<tr>
<th>Layer Description</th>
<th>MACT028.02</th>
<th>MACT057.60</th>
<th>BELL181.48</th>
<th>BELL194.60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballast</td>
<td>Thickness (m)</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Gravelly SAND</td>
<td>Thickness (m)</td>
<td>1.1</td>
<td>&gt;3</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>SPT N-value moisture content (%)</td>
<td>13</td>
<td>8 to 17</td>
<td>8 to 13</td>
</tr>
<tr>
<td></td>
<td>Gravel/sand/fines (%)</td>
<td>14</td>
<td>3 to 6</td>
<td>4 to 9</td>
</tr>
<tr>
<td>Sandy SILT (fill)</td>
<td>Thickness (m)</td>
<td>6 to 33</td>
<td>extends to base of embankment</td>
<td>8 to 14</td>
</tr>
<tr>
<td></td>
<td>SPT N-value moisture content (%)</td>
<td>8 to 17</td>
<td>17 to 29</td>
<td>10 to 35</td>
</tr>
<tr>
<td></td>
<td>Gravel/sand/fines (%)</td>
<td>2/30/68</td>
<td>0/15/85</td>
<td>3/17/80</td>
</tr>
<tr>
<td>Native Soil</td>
<td>sandy SILT</td>
<td>silty SAND</td>
<td>clayey SILT</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SPT N-value moisture content (%)</td>
<td>40 to 82</td>
<td>8 to 15</td>
<td>33 to 108</td>
</tr>
<tr>
<td></td>
<td>Gravel/sand/fines (%)</td>
<td>2/20/78</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.4 Trestle Condition

The location and condition of trestle elements was checked visually during the test pit investigation. The condition of the timber elements varied from sound to completely decayed with the majority of the timber elements encountered the test pits showing advanced pervasive decay. The decayed timber provided no resistance and typically disintegrated during excavation. Hand probing using a steel rod indicated that completely decayed timber in some areas extended to at least 9 m depth where vertical timber posts had been present. Steel fasteners (spikes and bolts) were also encountered during the excavations. Samples of wood from buried trestles were recovered during test pit excavation and were submitted for identification of the wood species. The findings indicated that the trestle had been constructed of Douglas fir. This species is not native to southern Ontario but was often used in wooden structures.

4 DISCUSSION

4.1 Sinkhole Formation

In most cases, the appearance of sinkholes at the ground surface has been noted in the course of routine daily track inspection, carried out by railway maintenance personnel. The dimensions observed varied with site conditions and weather conditions (frost, moisture etc), but generally the sinkhole diameters at time of initial reports range from 0.3 to 1.1 m. In one case (MACT057.6) where the trestle intercepted a concrete culvert the sinkhole diameter was approximately 2 m in diameter.
Processing and interpretation of the data by experienced personnel is required to separate electrical noise and reflections from extraneous objects such as buried boulders, and discarded rails, steel spikes or debris. The GPR images, produced after processing to remove noise and accentuate layering, show characteristic scattering hyperbolas at regular horizontal spacing and depth and were interpreted as representing the DBT elements. At about a third of the expected DBT bent locations, the hyperbolas were found to be within 1 m horizontal distance of timber elements exposed during subsequent test pit investigation. For another 22% of locations where definite hyperbolas were noted on the GPR, no test pit was excavated so the GPR results cannot be assessed. At about 45% of the test pit locations where DBT was encountered, well defined GPR hyperbolas were not identified. The GPR data was also reviewed to test for a relationship between strength of the reflective signal and the physical condition of the timber pieces, but no correlation was apparent.

3.2 Geotechnical Investigation Methods

A limited geotechnical site investigation was undertaken at each site to determine subsurface conditions and obtain definite information on buried trestle component locations and conditions. Two site investigation methods were utilized. The first method utilized auger boring equipment in conjunction with Standard Penetration Tests and supplemental dynamic cone penetration (DCP) tests to check density within the embankment fill and establish the elevation of the base of the embankment. The boreholes and DCP tests were carried out from the top of the embankment, between the rails. The second phase of site investigations was a test pit program commencing at sinkhole locations and proceeding to likely bent locations to directly establish the location and extent of the buried timber and to obtain additional geotechnical information on the embankment fill. The test pits were advanced from the top of the embankment at the edge of the ties.

Subsurface Conditions

The materials encountered within the embankments at all locations starting from the top of the embankment, consisted of the following sequence:
- Steel rails, wood ties and ballast,
- Gravelly sand (fill),
- Sandy silt (fill),
- Native fine-grained soil deposits.

Generalized embankment geometry and soil stratigraphy is shown in Figure 3:

![Figure 3: Embankment Geometry and Stratigraphy](image)

The bulk of the embankment below the ballast and gravelly sand layers consisted of sandy silt fill. Geotechnical parameters for various soil layers are shown in Table 1 below. The top of the buried timber trestle was encountered at depths varying from 1.0 m down to 3.6 m or the maximum depth of test pit excavation.

3.3 Site Information

Table 2 provides location, geological information, and specific construction history for each of the sites investigated and reviewed in this paper. The site naming is an abbreviation and concatenation of official railway locations. Thus for example, the first site is on the CPR Mactier Subdivision, at Mile 28.02, so is MACT028.02. The abbreviation BELL refers to CPR Belleville subdivision.
In spite of the widespread use of framed timber construction in railway construction throughout North America, we have been unable to locate other information on investigation and remediation of these structures, when they eventually deteriorate, and timber sections within embankments collapse. There is much empirical evidence that these failures are experienced regularly, but treatment has been localized to the ground subsidence location. There is some indication [Villard et al, 2000] that similar problem occurs in Europe. The voids and sinkholes are caused by karst geology, abandoned mines, and trench structures from the World Wars. The phenomena have been studied and remedial measures developed.

3 GEOTECHNICAL INFORMATION

The conditions encountered during the geophysical and geotechnical investigations of the five sites encountered relatively similar conditions at each of the sites. This is not surprising considering the fact that the five embankments were constructed in a short span of time between 1910 and 1915, are in the same region and used similar construction methods.

3.1 Geophysical Investigation

A number of geophysical investigation techniques were carried out at the sites to test the effectiveness at detecting and characterizing the presence of decayed buried timber trestle elements within railway embankments. Geophysical methods offer several advantages when compared to drilling or excavation. These include being non-destructive, non-intrusive procedures which can survey large area in a short period of time. Tests which have these traits are preferred to minimize disruptions when carrying out site investigation on active railway lines. The effective use of these methods for the detection of DBT depends in a large part on the operators expertise and the interpretation of the signals generated.

Ground Penetrating Radar (GPR) was employed at three of the sites to locate and characterize the DBT elements and provide information for targeting subsequent ground treatment options. The method utilizes pulses of electromagnetic energy that are transmitted into the ground at a pre-selected frequency. The electromagnetic energy is reflected from surfaces between materials with different dielectric constants. The travel time between emission of the wave and detection of the reflected waves is recorded. Conversion of the travel time to depth requires measurement or estimation of the velocity based on reflection from an object at a known depth. The measurements are repeated at user-selected intervals to form a 2 dimensional profile along the traverse line.

Careful selection of the electro-magnetic (EM) frequency is required to allow sufficient depth of penetration and reasonable resolution for the expected size of the timber elements. Generally lower frequency EM signals increase the depth of penetration but provide less spatial resolution reducing the ability to identify smaller objects. Several antennas with different frequencies were tested to determine an acceptable amount of resolution and sufficient depth of penetration to detect the DBT material. The depth of the top of the abandoned timber trestles at the site was typically at 1.5 to 3.0 m below base of rails and the width of the timber elements is typically 0.3 m to 0.4 m. For this physical scale, the frequency range which provides suitable resolution and depth of penetration at the site was found to be 100 MHz to 200 MHz. Higher frequencies were found to generate a significant amount of noise because of the presence of conductive materials within the ballast and the presence of small solid reflectors buried within the railway over the history of the property, and a high power GPR unit was required to achieve acceptable resolution because of the presence of these high conductivity materials.
Mactier Subdivision, near Bolton, Ontario. Initial plans were to excavate a short portion of the embankment, and reconstruct with geotextile and granular fill, through a depth of about 3 meters. When excavation was started, timber components of an abandoned trestle structure were found. Subsequent geotechnical investigation and archival research confirmed the existence of most of the timber trestle substructure elements. The bents are pier-type structures, constructed of timber posts, columns and horizontal cap elements. These bents were constructed from foundations (timber piles or spread footings) to a level where the superstructure elements could be supported to the designed track profile. Following the initial failure of decayed buried timber (DBT) elements in early 2005, 4 other sites were found as the result of DBT collapse, and sinkhole formation within a 50 mile radius of Toronto, by the end of 2006. Figure 1 shows these five locations.

![Figure 1. Locations of DBT sinkhole formation.](image)

2.1 Trestle and Embankment Construction

The particular method of construction was common during the initial development of railways in Canada during the 19th and early 20th centuries. A timber trestle structure could be constructed quickly to cross a valley, serve as falsework for permanent crossing construction, and then be filled by dumping from railway cars passing over the trestle. The technique is still in use to construct temporary railway structures, while heavy repairs and component replacements are effected.

The volume of buried timber within a trestle bent was estimated based on standard engineering plans and details shown in archival drawings for trestles constructed during the period. Based on this method, it is estimated that each bent was comprised of a volume of approximately 8 m$^3$ of solid timber pieces. At each bent location, this represents about 10% of the embankment material that directly supports the track structure and about 3% of the entire embankment volume.

Figure 2 is a photograph which shows a train-fill operation, in the process of filling in a timber trestle abandoned as a result of construction of a permanent bridge structure.

![Figure 2. Train fill burying temporary trestle substructure CPR Mileage 48.6, Parry Sound Subdivision.](image)

Based upon investigations at sites reported in this paper the superstructure (flexural members above the framed or pile trestle compression elements), was removed once fill reached the underside of the stringers. Final grading, track construction, and roadbed ballasting was then completed.
APPROACHES TO MITIGATING DECAYED BURIED TIMBER WITHIN RAILWAY EMBANKMENTS

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ABSTRACT

During the last three years, several sinkholes have been observed along CPR railway lines in Southern Ontario. The sinkholes have formed as a result of the decay of buried timber trestles in railway embankments. Although it has not occurred the sinkholes could result in hazardous changes in track geometry under load. This study summarizes the site investigation results and remedial methods implemented at five sites in southern Ontario. Remedial methods include placement geosynthetic reinforcement, soil-cement column reinforcement and grouting of voids at the trestle bents. The design, installation methods and construction constraints for the remedial options are described in this paper.

RÉSUMÉ

Depuis 2005, on a observé la formation des effondrements dans les remblais le long de lignes ferroviaires de CP dans l’Ontario-Sud. Le manque de support pourrait produire le changement de la géométrie de la voie ferrée. Les effondrements sont formés en raison de la détérioration des charpentes de bois enterrés dans. Cette étude récapitule les résultats de recherche de site. Les méthodes réparatrices ont inclus le renfort par géotextiles, par micro-pieux ainsi que le remplissage des vides avec un coulis cimentaire. La conception, les méthodes et les contraintes de construction pour les options réparatrices sont décrites en cet article.

1 INTRODUCTION

The decay of old abandoned wooden trestles buried within railway embankments in southern Ontario has resulted in formation of sinkholes at the top of embankments and localized loss of subgrade support for the railroad track bed. During 2005 and 2006 numerous sinkholes appeared at 5 separate railway embankments sites. The formation of sinkholes at track level is considered a hazard to railway operations and therefore site investigations and development of engineered solutions were implemented to address the hazards at these locations. This paper summarizes the results of the site investigations and development of engineering solutions that were implemented at each of the five sites. The paper also summarizes available background information on trestle and embankment construction methods, sinkhole formation mechanisms and possible sinkhole migration/triggering mechanisms.

2 BACKGROUND

In early 2005, a sinkhole developed in an active railway embankment on the Canadian Pacific,