Application of the Theory of Inventive Problem Solving in Tunnel Construction

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Abstract: Despite the importance of innovation in construction, there is no structured approach to systematically support innovation. The theory of inventive problem solving (TRIZ) provides a unique approach for structuring the development of innovative solutions for technical problems and has the potential for substantial results in construction innovation if used properly. This paper describes TRIZ and introduces its tools through applications in the field of utility tunnel construction. This paper describes how TRIZ tools can be used to generate conceptual solutions to a number of tunnel construction problems. In order to assess the practicality of the TRIZ analysis, the proposed solutions are compared to recent innovations in the field and actual solutions developed by experts. The comparison shows that although TRIZ tools were used by nonexperts in the tunneling field they included most of the features that exist in solutions developed by experts and were also able to point to technologies that are not yet widely used in the tunneling industry. The use of TRIZ in these applications showed that despite the advantages of the theory, further research and supporting tools are required to facilitate its day-to-day use in the construction industry.

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Introduction

Innovative solutions offer the potential for significant gains to individual companies, an entire industry, or society as a whole. Improvements in design, construction methods, products, and services decrease costs and delivery time while improving quality and safety. The search for creative solutions is always a critical step for technological improvement. Value engineering studies and constructability reviews usually include such a search. However, this search is not guided by clear directions and depends mainly on the expertise of the teams involved in the study in addition to other nontechnical factors. The search space is also limited by solutions within the knowledge boundaries of the industry. Solutions to similar problems that exist in other industries may not be easily identified.

To generate innovative improvements to technical construction systems, one must overcome two problems: (1) creating a business environment that motivates and adopts innovative solutions, and (2) managing the technical knowledge and expertise required to generate innovative solutions in a structured and systematic way without "re-inventing the wheel." The first problem is addressed by a number of researchers, as discussed in the following sections. The second problem is more challenging as there is no structured approach to be followed in realizing innovation, especially when solutions require crossing knowledge boundaries between different industries.

Structuring the development of technical solutions seems to contradict the concept of creativity and innovation. However, the theory of inventive problem solving (TRIZ) claims that similarities exist between innovative solutions and can be captured for re-use (Altshuller 1998). An example of this in the construction domain is demonstrated by three innovative techniques. First is the lift-slab construction method, where all slabs are cast one on top of the other on the slab-on-grade then lifted to their final elevation (Nawy 1997). Second is a method for constructing submerged pile caps where the caps are constructed above water level then submerged to their final position (Elazouni and Abd El-Razek 2000). Third is a method for erecting steel silos where the construction sequence starts at the top of the silo so that steel rings are always assembled on the ground (Elazouni 1997). Some similarities can be identified between the techniques used in each of these areas when stripping them of their details. For example, two similarities between the three cases are reversing the common construction sequence and pre-assembling components at the most convenient location, then transferring them to their final position. TRIZ attempts to formalize such similarities and organize them in the form of reusable tools.

TRIZ has been successfully applied in a number of industries to structure the innovation process. Major organizations like Ford, NASA, and Motorola make use of the theory in different formats to improve their processes and products (Savransky 2000). This paper explores the application of TRIZ to construction and in particular to the tunnel construction domain. The theory provides

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a structured approach for solving technical problems and makes use of cross-disciplinary knowledge for generating innovative solutions. This paper gives a brief description of the theory and then uses a number of TRIZ techniques to generate conceptual solutions and improve work methods within the tunneling domain. The use of these tools reveals some of the strengths of the theory and highlights some of the potential areas for further research to make the theory usable in day-to-day technical decision-making in construction.

This paper describes three case studies related to the guidance system of tunnel boring machines (TBMs), the limited space of undercut area, and the handling of large diameter pipes. The area where innovation is desired is explained followed by an application of a number of TRIZ tools to realize innovative solutions in the area. To assess the practicality of the theory, the generated solutions are compared with expert-developed solutions and relatively new (cutting edge) technologies that deal with the problems. An overall discussion is then presented highlighting the realized advantages and disadvantages of the theory.

Background

Innovation in the Construction Environment

Innovation has many benefits, including increases in economic growth and productivity resulting from the introduction of new or improved products and services. Construction innovation in particular may also provide social benefits by reducing the costs of constructed facilities and making them affordable for a greater proportion of the population. Innovations also increase the technical feasibility of construction projects that would otherwise appear beyond the technological barrier. They may also provide nonmonetary benefits for companies in the form of better competitive position and improved reputation (Slaughter 1998).

Innovation plays an important role in improving constructability of the project during the different phases of a construction project life cycle. However, according to the Construction Industry Institute (CII), its role is magnified during field operations: "Constructability is enhanced when innovative construction methods are utilized" as a principle for improving constructability during field operations (CII 1986). Although the impact of innovative modifications during field operations is less than the impact of modifications made during conceptual planning or design, it is still considered significant (O'Connor and Davis 1988). A study by Jergeas and Van der Put (2001) shows that the "use of innovative construction methods" is an area that has a large gap between the *potential* and *actual* benefits of application. Among the application barriers identified in that study are the lack of knowledge of the latest construction methods and techniques and the organizational resistance to changes.

There is some disagreement as to what is considered an innovation. Innovation can be subjectively defined as "methods that are not generally considered common practice across the industry and are generally creative solutions responsive to field challenges" (O'Connor and Davis 1988). This definition includes adoption of recent high-tech advances and nonconstruction technologies. According to Slaughter (1998), an innovation does not necessarily mean an invention. By contrast, it does not require a detailed design or physical manifestation and it does not have to be novel with respect to the existing arts, but only to the creating institution (Freeman 1989; Slaughter 1998). The definition given by O'Connor and Davis is adopted in this study along with an addition from Slaughter's definition that the innovative method or solution need only be novel to the creating institution and not necessarily to the whole industry. Hence, an innovative solution is a method that is not considered common practice across the creating institution.

Research deals with construction innovation from different perspectives. One approach investigates the requirements for creating an innovation-friendly business environment that encourages and adopts innovative solutions. Samples of this approach can be found in: Tatum (1984, 1986, 1987), Nam and Tatum (1992), Slaughter (1998), and Koskela and Vrijhoef (2000).

Another approach focuses more on the knowledge acquisition aspects of innovation. One study that follows this approach was conducted by Toole (2001) which shows that successful innovative building products follow four technological trajectories and that the success of future innovative products can be predicted by evaluating their progress along those four trajectories (Toole 2001). Another study by Kangari and Miyatake (1997) shows that effective information gathering is one of the key elements that contribute to the development of innovative construction technologies in Japan. That study also concluded that a crucial link between innovation and business strategy in a large construction firm in Japan was found to be the long-range technology forecasting that integrates "action of today with the vision of tomorrow" (Kangari and Miyatake 1997). A third study shows that U.S. project managers rely heavily on trade magazines and conversations with internal colleagues for information about innovations and that firm's efforts to facilitate information seeking by their project managers focus primarily on information from internal sources, through reports of "lessons learned" and other means (Veshosky 1998).

Theory of Inventive Problem Solving

Although the scope of the study by Toole (2001) is limited to one type of design product and only in the construction domain, the argument that successful innovations follow predictable paths is consistent with the discoveries of Altshuller (1998). Through the study of patents, he realized that technical systems, in general, evolve according to regularities, which are generic for all engineering domains. These regularities can be studied and used for innovative and inventive problem solving, as well as for forecasting the further evolution of any design product in design terms (Savransky 2000).

Altshuller originally developed TRIZ in the mid-1950s. TRIZ is based on his study and analysis of patents in different technological fields. Altshuller (1998) studied more than 400,000 patents in deriving this theory. To date, TRIZ specialists have analyzed approximately 2 million patents. The analysis of these patents in the different engineering areas resulted in several important discoveries, which form the theoretical basis of TRIZ and can be summarized as follows: Technological systems evolve not "accidentally" but in accordance with certain patterns. These patterns can be revealed from the world's accumulation of patent information, and intentionally applied for the purpose of advancing a system through its evolutionary stages (Altshuller et al. 1999). These patterns can be used to solve difficult problems, forecast the evolution of technological systems, and create and enhance the tools used for inventive problem solving.

Based on this concept, some tools were developed for systematic analysis of inventive problems. Examples of these tools are evolution patterns, contradiction matrix, physical contradiction resolution principles, substance field (su-field) analysis, and ideal

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Parameter to be improved		Parameter that is getting worse				
	Engineering Parameters	27 Reliability	28 Accuracy of Measurement	29 Accuracy of Manufacturing	30 Harmful factors acting on object from outside	31 Harmful factors developed by an object
23	Loss of Substance			35, 10, 24, 31		
24	Loss of Information					
25	Waste of Time	10, 30, 4	24, 34, 28, 32	24, 26, 28, 18	35, 18, 34	35, 22, 18, 39
26	Amount of Substance			33, 30		
27	Reliability	Physical Contradiction		11, 32, 1		
28	Accuracy of Measurement		Physical Contradiction	-		

Resolution Principles	23) Feedback 24) Intermediary 25) Self-service	26) Copying 27) Inexpensive short-lived objects 28) Mechanics substitution

Fig. 1. Contradiction matrix sample

final result (IFR). To illustrate how these tools work, the following briefly describes the contradiction matrix as one of the popular and easy-to-use tools of TRIZ. More details on other tools can be found in the work of Altshuller et al. (1999), and Savransky (2000).

Contradiction matrix: A technical system has several characteristics (e.g., weight, size, speed, reliability, etc.) that describe its physical state. When trying to improve one of these characteristics (parameters), other characteristics may deteriorate as a result. In such a situation a technical problem (technical contradiction) arises and calls for a solution. Conventional solutions usually propose a compromise between the "improving" and "deteriorating" parameters. An innovative solution is achieved by resolving the technical contradiction without introducing a compromise (Altshuller 1998).

Altshuller identified 39 system parameters as being most often associated with technical contradictions. He also identified principles that were similarly used in patents from different fields to resolve the contradictions that occur between any pair of these parameters.

The result is a contradiction matrix, which is formed by placing these engineering parameters in rows and columns. Each cell in the matrix represents a particular technical contradiction, and contains a set of numbers that corresponds to a set of inventive principles that have been successfully applied to resolve the contradiction (Altshuller et al. 1999; Savransky 2000). Fig. 1 illustrates an area of the matrix in tabular form.

The first step in using the matrix is to analyze the problem at hand and to identify its components and their respective functions. The next step, subsequent to an analysis of the problem, is to formulate the contradictions in terms of standard TRIZ parameters. A contradiction is recognized if improving one characteristic results in the deterioration of another and vice versa. For example, a surveying activity is essential to guarantee accuracy of construction but, at the same time, it will result in the delay of several other activities. Such a conflict could be formulated as a contradiction between two standard parameters: parameter number 25 (waste of time) and number 29 (accuracy of manufacturing). As shown in Fig. 1, the intersection between the row and column, which represent the two parameters, results in a cell that contains a particular set of numbers. The parameter numbers refer to those principles most commonly used for resolving this type of contradiction; they are ordered by their frequency of use. In this example, the principles employed are: 24) intermediary, 26) copying, 28) mechanics substitution, and 18) mechanical vibration. These principles represent potential directions for finding solutions. The problem solver uses these directions to generate detailed solutions that will meet the specific configurations of the problem. Further explanation and sample uses of each principle are given in TRIZ literature. For example, principle number 26 (copying) is further explained as: replace an object by its optical copy or image (Altshuller et al. 1999). Materialization of this principle in the construction surveying domain can be found in the form of laser scanning and photogrammetry technologies. More detailed cases illustrating the use of TRIZ are presented in the following sections.

The Theory of Innovative Problem Solving Application in Utility Tunnel Construction

Description of the Tunneling Process

Tunneling projects involve three main processes: excavation, dirt removal, and tunnel support. The process of tunnel construction commences with the excavation and liner support of a vertical shaft to a depth corresponding to the invert level of the tunnel excavation. The other typical tunnel activities are excavation and support of the undercut area (an enlargement at the bottom of the shaft used for staging material handling and dirt removal operations), excavation of the tunnel and tail tunnel, disposal of dirt from the tunnel face, hoisting the dirt to the ground level, lining the tunnel, extending the services and rail tracks, and the excavation and support of the removal shaft (if a TBM is used).

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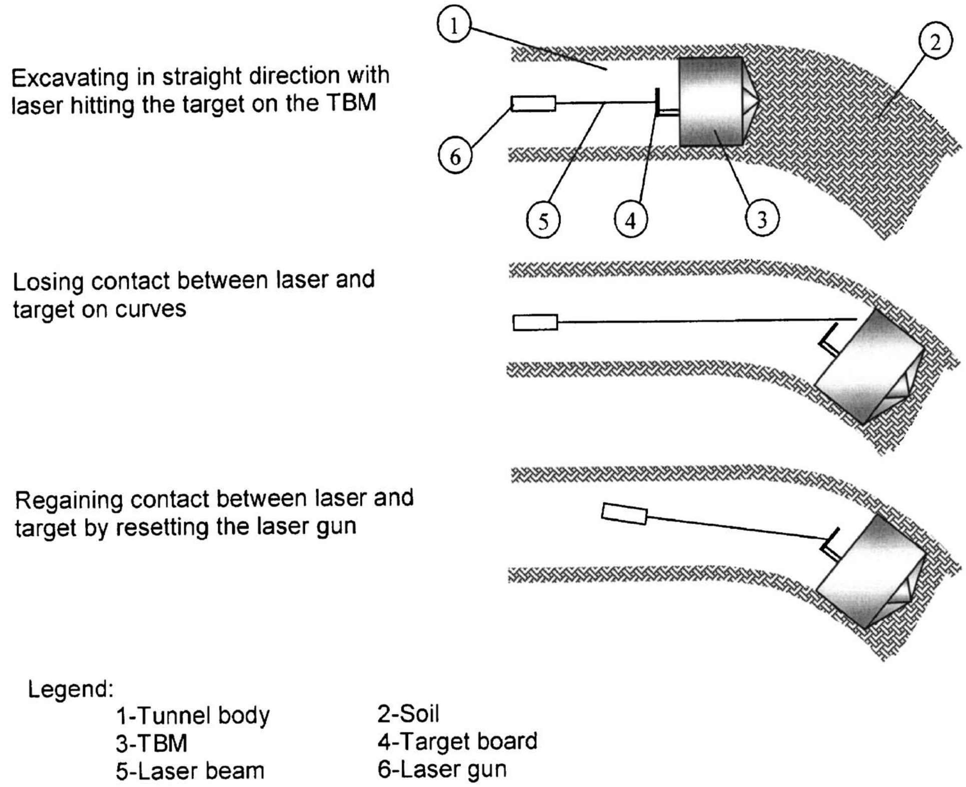

Fig. 2. Illustration of tunnel boring machine alignment problem

During TBM excavation, a system for dirt removal works in parallel to remove the dirt out to ground level. One or more trains of muck cars are usually used for that purpose. The cars are loaded with dirt at the tunnel face, travel to the undercut area, and get dumped at ground level using a crane. If more than one train is used, the undercut area should be arranged to allow switching between empty and loaded trains and muck cars.

The remainder of this paper demonstrates the use of TRIZ to conceptualize solutions to problems associated with TBM utility tunneling. The main objective of this discussion is to explore the effectiveness of applying TRIZ for solving common technical problems in particular, rather than for solving particular major or significant problems.

Case Study 1: Enhancing Tunnel Productivity through Innovations in Tunnel Boring Machine Guidance System

Problem Description

The overall production rate of the tunneling process depends on synchronizing all tunneling activities to maximize the utilization of resources and minimize the waiting times. When activities fall off the synchronized pattern, the production rate gradually drops. A study undertaken by Mohamed and AbouRizk (2001) revealed that the elimination of the surveying cycle would result in a 0.9 m/shift increase in production for a typical 3 m diameter tunnel with an average advance rate of 8 m/shift. A simulation model for an actual tunneling project used in that study showed that the survey time had the most significant effect on the overall production among other secondary factors (i.e., excluding TBM, crew, ground conditions) that affected the project. Therefore, improvement of the TBM guidance system to reduce surveying times was considered feasible for further investigation.

The TBM alignment problem emerges from trying to maintain the correct path for the TBM at all times. As shown in Fig. 2, when the TBM hits a curve in the tunnel path, the laser beam deviates from the target and a surveying crew has to reset the gun to ensure correct alignment of the TBM. The resetting process requires suspension of the excavation operation because the TBM cannot be operated without proper alignment with the tunnel design path, and the survey crew occupies the tracks that lead to the tunnel face.

Application of the Theory of Inventive Problem Solving Tools

TRIZ's contradiction matrix tool is applied to this problem to produce a conceptual solution. As illustrated in Fig. 3, TRIZ tools provide a solution by re-formulating the problem into a generic form, which should not use any domain-specific terminology. One of the advantages of this approach is that it frees the problem

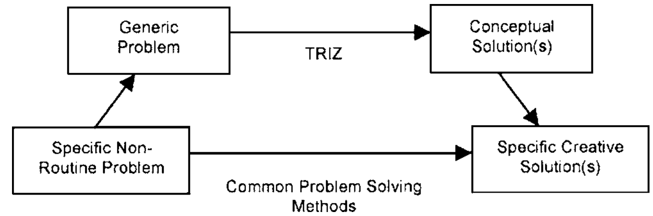

Fig. 3. Theory of inventive problem solving versus common problem solving approaches (Savransky 2000)

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solver from "psychological inertia," which is the unconscious tendency of the solver to limit his or her conceptual boundaries by the meanings of the words used for describing the problem (Savransky 2000). Once a generic problem is formulated, a number of principles or standard solutions are suggested for solving it. These solutions act like pointers to conceptual solutions for the original problem.

When using the contradiction matrix, the generic problem should be formulated in the form of one or more contradictions that take place between different parameters of the system. In this case, the goal of the TBM alignment system is to make sure that the TBM is excavating in the right direction.

However, to achieve the above goal, the system has to be adjusted from time to time to correct the path of the TBM when it curves or gets misaligned for any other reason. The adjustment process forces a complete shutdown of the excavation process. The contradiction in this situation is between the accuracy of TBM excavation and the wasted time due to resetting the laser alignment system. The generic engineering parameters defined in the matrix that correspond to this situation are parameter number 25 (waste of time) and parameter number 29 (accuracy of manufacturing).

The problem can then be described in generic terms as follows: In order to improve the wasted time in the system, the manufacturing process becomes less accurate. As shown in Fig. 1, a contradiction is represented by the "improving engineering" parameter defined in the horizontal direction and the parameter which worsens, which is defined in the vertical direction. The intersection of these two parameters defines a cell in the matrix that contains a number of principles that are mostly used to resolve that contradiction. Explanations and examples of conceptual solutions based on these principles are also provided in the TRIZ literature. The principles shown in Fig. 1 are suggested by the matrix to resolve the contradiction between waste of time and accuracy of manufacturing (see Table 1).

Table 1. Resolution Principles for the Tunnel Boring Machine Guidance Problem (Altshuller 1998)

Resolution principle	Explanation
24) Intermediary	• Use an intermediary carrier article or intermediary process • Merge one object temporarily with another (which can be easily removed)
26) Copying	• Instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies • Replace an object or process with optical copies • If visible optical copies are already used, move to infrared or ultraviolet copies
28) Mechanics substitution	• Replace a mechanical means with a sensory (optical, acoustic, taste, or olfactory) means • Use electric, magnetic, and electromagnetic fields to interact with the object • Change from static to movable fields, from unstructured fields to those having structure • Use fields in conjunction with field-activated particles (e.g., ferromagnetic)
18) Mechanical vibration	• Oscillate or vibrate an object • If oscillation exists, increase its frequency • Use an object's resonant frequency • Use piezoelectric vibrators instead of mechanical ones • Use combined ultrasonic and electromagnetic field oscillations

Generating Solution Concepts

Based on the principles suggested to resolve the generic contradiction, a number of concepts can be derived to resolve the TBM guidance problem. These concepts are listed in Table 2 and are categorized by the principles that led to them. The following set of concepts can be summarized from the previous analysis to produce a more evolved TBM guidance system:

1. A system with increased automation and less human involvement. The resetting process in the current system is the component that has the highest human involvement and therefore has the highest potential for automation.
2. A system that consists of a larger number of intermediate, independent, and more controllable subcomponents. The current system has a laser gun that is fixed in one location until adjusted during the resetting process. A more evolved system may have a more controllable laser gun and may also have some adjustable prisms that carry the laser between the laser gun and the TBM.
3. A system that depends on a different type of field that is more controllable and flexible in order to follow the TBM's movement. The use of sound or ultrasound waves is suggested for investigation.

The previous characteristics represent directives for generating new design improvements for the TBM guidance system. Guided by such directions, an expert or group of experts in the surveying field and TBM guidance instrumentation should be able to produce detailed implementations in a structured format, instead of following random paths. The following section shows how these guidelines compare to the current state-of-the-art in TBM guidance.

Current Advancements in Tunnel Boring Machine Guidance

An investigation of the state-of-the-art in technologies in TBM guidance systems by Mohamed (2002) revealed that advancements in TBM guidance support the above-mentioned conclusions. In particular, available systems have different features that comply with the characteristics identified using TRIZ in the following aspects:

1. Higher degree of automation: All of the laser-based systems depend on a laser theodolite instead of a laser gun. The theodolite can be manually or automatically adjusted by a central processing computer system that manages the resetting

Table 2. Concepts Generated from the Contradiction Matrix

Principle	Conceptual solution
24) Intermediary	• Use carriers in between the laser gun and the target that can be easily adjusted to trace curves
26) Copying	• Instead of interacting with the TBM itself, interact with a copy of its coordinates • Use a copy of the surveying crew to do the resetting (automate the resetting process)
28) Mechanics substitution	• Use different kind of fields other than laser to detect the actual and design coordinates of the TBM; that field should be more controllable
18) Mechanical vibration	• Use sound or ultrasound waves to detect the location of the TBM

Note: TBM=tunnel boring machine.

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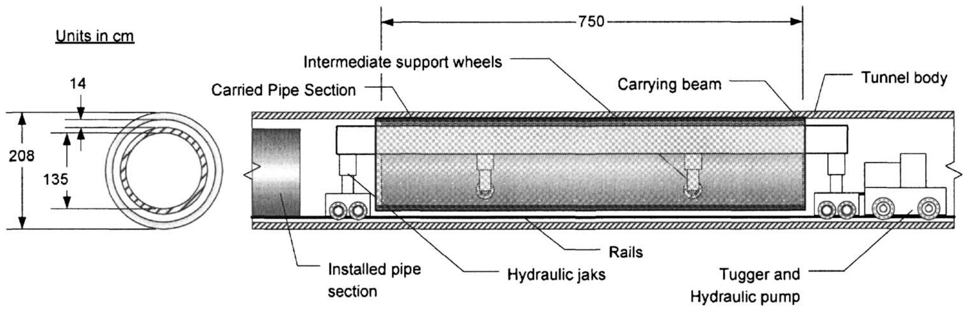

Fig. 4. Pipe carrier solution

and repositioning of the laser theodolite in addition to the deviation of the TBM from the designed alignment.

2. Intermediate, independent, and more controllable subcomponents: Some of the laser-based systems include a remote prism that acts as a base-point for the laser theodolite. The theodolite follows the movement of the TBM but uses the remote prism as a permanent guide to determine its exact position.
3. Use of a different field that is more flexible and controllable: A different category of guidance systems uses gyroscopes and accelerometers instead of lasers to detect the movement of the TBM relative to its original position. This category represents a manifestation of a "use of different field" direction suggested from the contradiction matrix.

At the time of writing there is only one company that manufactures these systems for tunnel construction and their system is not yet used by any tunnel builder.

Case Study 2: Installing Large Diameter Pipes into the Finished Tunnel

Problem Description

In the Rossdale Water Intake tunnel constructed by the City of Edmonton, prefabricated pipes had to be installed inside a utility tunnel after it had been completely excavated and lined. Each pipe section had a length of 7.5 m, a 1.35 m inner diameter, and a 10 cm wall thickness. The tunnel is supported using steel ribs with an outer diameter of 2.08 m. This configuration resulted in an average clearance of 14 cm between the outer diameter of the pipes and the inner diameter of the ribs as shown in Fig. 4. Moving the pipes to the tunnel entrance area was not a problem as it was an open excavation pit with an area of 10.7 m in length and 7.3 m in width. The problem was how to carry and install such large pipe sections with the available tight clearance.

Application of the Theory of Inventive Problem Solving Tools

The main conflict in this problem is due to the limited workspace. In other words, the use of traditional pipe handling equipment becomes inconvenient because of the limited workspace. Using TRIZ's contradiction terms, the problem can be generically formulated as contradiction between 7) volume of mobile object and 33) convenience of use, or 5) area of mobile object and 33) convenience of use. The area is assumed as a parameter in this case because of the tight clearance between the cross-sectional area of the tunnel and that of the pipe. Using the contradiction matrix, five principles are suggested for resolving the above contradictions. These are: 15) dynamicity, 13) do it in reverse, 17) transition into new dimension, 30) flexible films or thin membrane, and 12) equipotentiality. Standard explanation of these principles can be found in Altshuller (1998).

The actual solution designed and used by the City of Edmonton for this problem is illustrated in Fig. 4. The solution includes a specially designed pipe carrier that holds the pipe section from the inside and lifts it slightly enough to clear the rail tracks. Once the new section is moved close enough to the last installed section, the carrier moves down until it rests on a set of intermediate support wheels. The front boogie assembly is collapsed and moved into the installed section. With the front of the carrier supported inside the last installed section, the carrier moves the new section into position.

The previous solution shows typical implementation of principles 15, 17, and 12 listed in the previous sections. The carrier works from the inside area of the pipe instead of the common outside (principle 17, new dimension). The carrier depends on a number of hydraulic jacks that change positions relative to each other to adapt to the position of the pipe (15, dynamicity). The carrier also uses minimal raising and lowering of the pipe (12, equipotentiality).

Most of the principles suggested from the matrix match the concepts used in the actual solution of the problem, which indicates that using these principles might enable an engineer without extensive experience in material handling equipment to probably reach a similarly effective solution.

Case Study 3: Dirt Removal in an Undercut Area of Limited Space

Problem Description

During the underground construction of the light rail transit (LRT) system in downtown Edmonton, one of the main problems was the dirt removal. The undercut area of the tunnel had a limited space that did not allow using common undercut layouts. Fig. 5 shows a typical undercut layout and the layout in the LRT tunnel case. In the typical case, a tail tunnel is excavated at the back of the undercut area. The train of loaded muck cars moves into the undercut allowing one muck car to be positioned under the shaft opening. Once the muck car is dumped, the train moves to allow the next loaded car to dump. The tail tunnel in this case allows the empty cars to move back, freeing space for the loaded ones. The tracks are usually positioned directly under the shaft opening so that a crane can easily move the muck cars.

In the LRT case, a parking lot located at the back of the undercut area prevented the excavation of a tail tunnel. In addition, the only shaft opening that could be used for moving dirt was not

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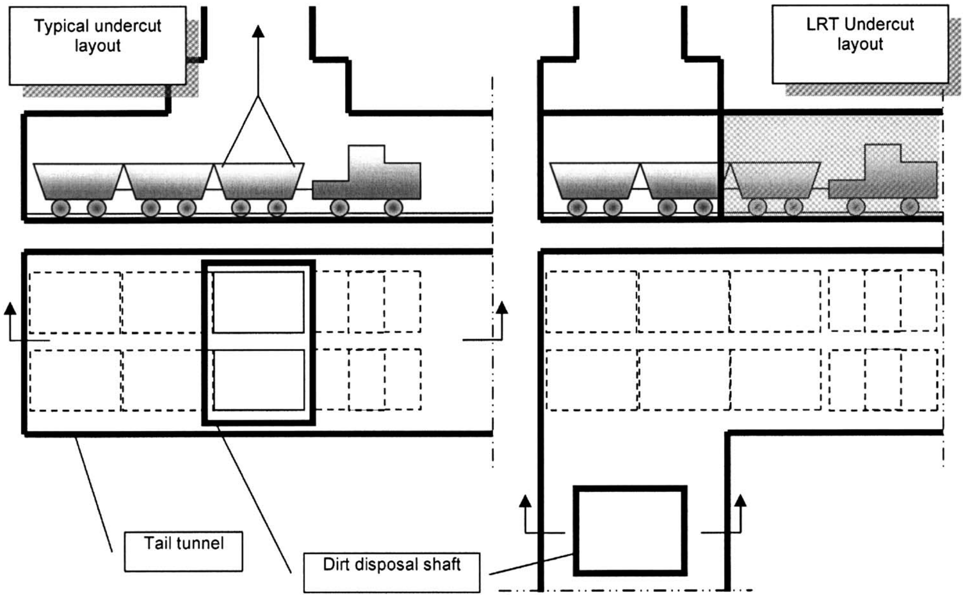

Fig. 5. Typical undercut layout versus light rail transit case layout

directly positioned over the tracks. The muck cars available for use are equipped with a dumping mechanism that allows them to flip their bucket and dump their load into a sump without being removed from the tracks. A crane hoists the sump to the ground level. The capacity of the sump is equivalent to the capacity of one muck car.

Application of the Theory of Inventive Problem Solving Tools

The contradiction matrix is used for analyzing the dirt removal system in this problem. The main goal of the system is to dump the loaded muck cars and make them ready to move to the tunnel face as fast as possible. By examining the changes from the normal undercut layout and the one that exists in this case, it is obvious that the length of the tracks became shorter, the area of the system as a whole became smaller and the shape became different. Each of these parameters negatively affected the productivity of the system. This leads to three pairs of TRIZ contradictions. Table 3 shows a list of these contradictions together with the principles proposed from the matrix to resolve them.

Table 3. Contradictions in the Light Rail Transit Undercut Problem

Improving parameter	Deteriorating parameter	Principles
4) Length of stationary object	39) Capacity/ productivity	30) Flexible films or thin membranes 14) Spheroidality 7) Nesting (Matrioshka) 26) Copying
6) Area of stationary object	39) Capacity/ productivity	10) Prior action 15) Dynamicity 17) Transition into new dimension 7) Nesting (Matrioshka)
12) Shape	39) Capacity/ productivity	17) Transition into new dimension 26) Copying 34) Rejecting and regenerating parts 10) Prior action

The suggested principles were used to conceptualize solutions without knowing the actual solution that was used on site. All possible solution concepts were generated first before examining them against the detailed dimensions and geometrical constraints of the site. These concepts are generated by trying to apply the principles either to each individual component (e.g., tracks, muck cars, or sump) of the system, to the system as a whole, or to a group of components. The following sections describe some of these concepts. The first two concepts were geometrically possible to fit into the actual dimensions of the undercut. The remaining concepts were not possible.

Concept 1

Using the principles of spheroidality, dynamicity, and new dimension, a rotating disk is to be added at the last section of tracks. The muck car is to be dumped to an opening on one side of the disk. The dirt would then be transferred down a slope under its own weight to the sump. The disk would rotate the empty muck car 180° off the incoming track and replace it back on the outgoing track. The sump in this case needs to be located at an elevation lower than the lowest point of the slope. A modification of this concept includes using a section of the track at a 90° angle from the incoming tracks. In this case the disk rotates only 90°. The muck car moves to the cross-track section and dumps directly to the sump. Then it moves back to the disk, which rotates the remaining 90° to the outgoing tracks. Fig. 6 illustrates this concept.

Concept 2

Using the same principles as in concept 1, the one rotating disk may be replaced by two smaller ones. Disk 1 rotates the loaded car off the incoming track and sets it on the cross tracks. The muck car dumps to the sump and moves back to disk 2, which rotates to align the car with the outgoing tracks.

Concept 3

"Nesting" was repeated twice in the proposed principles from the matrix. Based on this principle, the limited length of the tail tracks can be overcome by nesting the muck cars once they are

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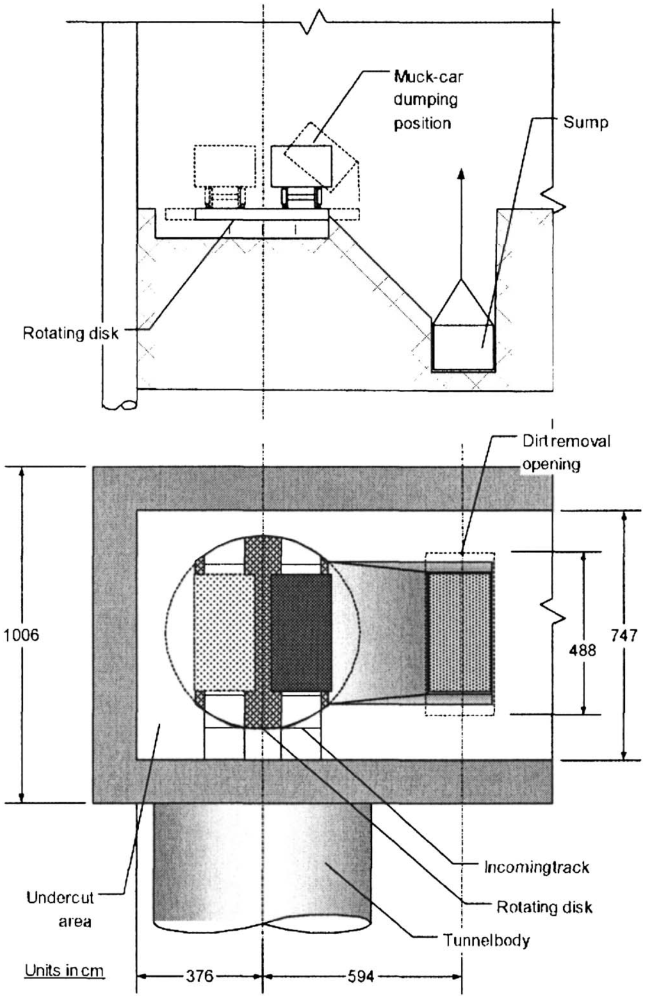

Fig. 6. Concept 1: One rotating disk

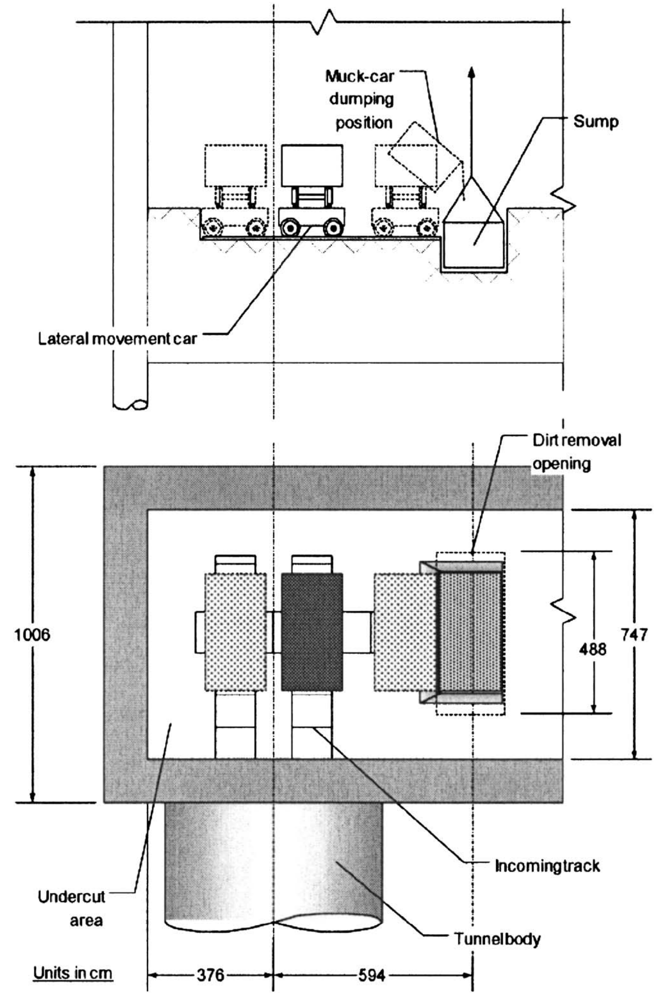

Fig. 7. Actual solution of the light rail transit undercut problem

empty. This would call for a change in the design and shape of the muck car. A design similar to that of shopping carts can be used to significantly reduce the tail tunnel length required for storing empty muck cars. In the LRT case, the allowed space at the back of the undercut was so limited that it could not even accommodate nested cars. In addition, the problem of transferring dirt to the sump would still remain unsolved. However, the concept remains quite possible to apply in the normal situations, in which case, a considerable reduction in the tunnel tail length can be achieved.

Concept 4

This concept depends on the principle of "transition into new dimension." It suggests having an overhead crane that moves the muck cars laterally between the incoming track, the sump, and the outgoing track. This concept was rejected because there was a constraint that calls for freeing all the space above the muck cars for material handling operations.

Actual Solution Used for the Case

The actual solution used by the City of Edmonton is shown in Fig. 7. In this solution, the last section of the track, which carries the loaded muck car, is allowed to move sideways. The whole section of the track with the muck car on is carried by a movable carrier. The carrier moves sideways on a second set of tracks located at a lower level underneath the undercut area. First, the track section is moved with the loaded muck car to the sump where the muck car dumps directly to the sump. The carrier then moves back to line up with the outgoing tracks and the empty muck car is released there. The solution obviously makes use of the principles of dynamicity by allowing the tracks to move sideways instead of being fixed, and transition into new dimension by utilizing another plane at a lower level for the movement of the muck cars.

Case Discussion and Comments

Although the writers are not experts in tunnel construction, the use of TRIZ principles allowed the generation of a number of possible solutions. Further, the actual solution that was developed by an expert utilizes two of the suggested principles. It is therefore assumed that by using the TRIZ analysis approach for solving innovative problems, an expert or group of experts would be able to generate more effective solutions in a systematic manner. Following the systematic approach of TRIZ is also useful in generating several alternative solutions to the problem. Although some of these solutions may not be feasible for a particular case, they may be effective in others (e.g., nested muck cars).

The case, however, also points to the level of difficulty associated with formulating the contradictions in the problem. In this case, all possible contradictions were formulated and all the sug-

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gested principles were examined in order of their frequency of suggestion by the matrix, which can be a useful approach to overcome this difficulty.

Overall Discussion

Advantages of the Theory for Inventive Problem Solving Approach

The use of the TRIZ tools for analyzing tunneling problems showed that the tools gave useful principles that lead to possible solutions. The principles are generic in nature and require the use of creative analogy to transfer them into problem-specific solutions. Significant similarities were found when comparing actual solutions with principles suggested from TRIZ tools. This shows an advantage of TRIZ's approach, which is the ability of guiding the problem solver towards the most effective solutions for a problem. This guidance should minimize the randomness in the search and systematize and focus the efforts of the experts on the most promising and effective solution paths.

In some cases, TRIZ principles actually pointed to solutions that are not yet used in the industry (e.g., inertial navigation). This shows another advantage of TRIZ, which is the use of multidisciplinary knowledge in suggesting solution principles and the ability to foresee improvements beyond the boundaries of the industry domain knowledge. Although some principles and suggestions may seem to be "out-of-context," further pursuing of search along their path may reveal highly effective solutions. Such solutions may not be obvious at the beginning only because they lie outside the domain of knowledge of the problem solver (e.g., replacing the laser field in TBM guidance).

Another advantage of TRIZ is its seamless generic approach for consolidating knowledge that can be reused for solving a wide spectrum of technical problems. The fact that TRIZ tools depend on a finite number of solution principles and heuristics suggests an opportunity of following a similar approach for guiding the solution of nontechnical problems as well.

Disadvantages and Future Research

Despite the discussed advantages of TRIZ, a number of areas need to be researched in order to make use of it in the day-to-day decision-making process in construction. One of these areas is the problem formulation. An ill-defined problem means a misleading set of principles. Therefore, some tools are needed to highlight the main contradictions in a situation and facilitate an accurate formulation of the problem.

Another area requiring more research is the transformation of the generic principles into problem-specific solutions. This process depends mainly on the ability of the problem solver to analogically generate solutions from his/her domain of knowledge that comply with these principles. A knowledge base of domain-specific sample solutions that illustrates the different principles would provide a useful source of examples that help trigger more analogical solutions. A third area is quantitative assessment of feasibility of a solution. When new solutions are conceptualized, the feasibility and risks associated with these solutions have to be assessed especially when such solutions represent parts of a superior system. In such cases, tools are needed to test the impact of the new solutions, which may not yet exist in reality, on the overall existing system. In the TBM guidance and LRT undercut case, this assessment would answer questions like: how much time can be saved by using the new system? or what would be the overall tunnel production rate if the new system is used?

Finally, TRIZ provides a "step-by-step" algorithm known as *ARIZ* for solving any technical problem (Savransky 2000). The algorithm combines the different TRIZ tools and navigates through them to reach a solution. However, the algorithm is fairly complex and requires a user possessing intensive training and a deep knowledge of all the TRIZ tools, which makes the algorithm impractical for use in solving construction problems. A similar but simplified approach needs to be formulated to suit the needs of the construction domain.

Conclusions

This paper introduced the theory of inventive problem solving (TRIZ) through applications in the field of utility tunnels construction. The theory is applied in its native form to a number of problems. TRIZ's contradiction matrix tool was used to generate conceptual solutions for these problems. A comparison between the suggested solutions and actual or existing solutions showed that they closely match each other. The resolution principles suggested from TRIZ were able to point to most of the features that existed in the actual solutions. They were also able to point to solutions that are not yet widely used in the tunneling industry although successfully used in other disciplines like military and oil industry. The sample applications show a potential for TRIZ use in improving construction innovation. Despite the advantages of the theory, further research and tools are required to facilitate its day-to-day use in the construction industry. These tools include problem formulation tools, solution testing and analysis tools, and knowledge consolidation tools.

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