VACUUM GROUTING REPAIRS FOR EXISTING POST-TENSIONED STRUCTURES AND NEW CONSTRUCTION

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ABSTRACT: Vacuum grouting repairs have become a necessity in bridge repair and in new construction of post-tensioned structures. Once only performed by specialty contractors, vacuum grouting can now be performed by a qualified grouting technician employed by the general bridge contractor or precast manufacturer. In new construction, it is occasionally required to perform vacuum grouting repairs to a duct that, for a variety of reasons, require this repair technique. A partially filled duct due to a malfunctioning pump, or blockage; or a crushed or lost vent tube can delay completion of tendon. Much time can be lost if repairs are not accomplished in a timely manner. Parts for a vacuum grouting system can be secured from numerous national and local vendors and a rugged system can be assembled within a day at a very reasonable price. It is imperative the grouting technician and inspector understand the basic fundamentals of how and why vacuum grouting works. Vacuum grouting is not a cure-all for poor workmanship or design, but in the hands of skilled technician, can repair many problems once requiring tear out and/or replace techniques.

Many advances have been made in vacuum grouting techniques in the last five years. Larger, faster vacuum pumps have been utilized. Digital direct read-out void measuring equipment is available. Electronic grout flow meters can read grout volumes placed into voids. Borescopes have been used to visually inspect voids. Ultrasonic, ground penetrating radar (GPR) and pulse-echo technologies, among others, have been used to locate voids. Although technology has made major advances on the forensic investigation of voids, a thorough understanding of post-tensioned construction and design is an absolute necessity to understand the nature of repairs. Vacuum grouting is one repair technique that bridge builders and repair specialists need in their toolboxes.

Keywords:

Vacuum Grouting, Bridge Repair, Post-Tension, Voids, Ducts,

Background:

Little has been written about vacuum grouting repairs. It was been the understandable objective of the specialty repair grouters to keep this information secretive. A search on the Internet reveals only self-promoting contractor project information and Florida Department of Transportation (FDOT) and Federal Highway Administrations (FHWA) specifications. This paper will discuss the reasons these repairs are performed; what works well and not-so-well, and recent advances. Most knowledge gained has been empirical, created by the ingenuity of field personnel.

Bonded post-tensioned tendons are filled with a cementitious grout for two primary reasons. First is structural continuity. The second is corrosion protection of the post-tensioned steel. This is the focus of this article.

In the late 1990's, this author, along with a post-tension engineer, inspected Mid Bay Bridge in western Florida. Walking in a dark box culvert 50 feet above water, we encountered a post-tensioned anchor head lying on the concrete surface. All of the connecting strands were severely corroded. Further inspection revealed this anchorage was at one end of six major external longitudinal tendons holding this precast segmental bridge span together. This represented a 16% loss of capacity, a major structural problem. Other deficiencies were noted- split plastic duct and poor grout quality. These deficiencies were rectified in subsequent repair contracts.

Further along in this field investigation led to eastern Florida, where pre-published photographs of major loop tendon failure inside Sunshine Skyway Bridge were viewed. These failures were in the bridge columns supporting the approach roadway above Tampa Bay. Vertical loop tendons had corrosion exceeding 10% of their overall length. In less than twenty years, this bridge built to last 100 years required major structural repair. The many of the strands were completed corroded.

Florida Department of Transportation, as the nation's largest owner/builder of post-tensioned bridges, undertook a major inspection program of their bridges to identify any issues. The national post-tension system manufacturers, engineers and grout manufacturers, along with the American Segmental Bridge Institute (ASBI) jumped on board to help identify, re-engineer and rectify the issues at hand. Previously, post-tensioned bridge failures in the United Kingdom had mandated a 10 year moratorium on this type of construction in that country, and this situation was not wanted in the United States. Inspections of other post-tensioned structures indicated similar problems with grouting.

In past (pre 2000) grouting was often relegated to the 'low man on the totem pole'. Grouting was often viewed as a dirty, unsophisticated necessary evil. Inspection was often lax and quality control was non-existent or not enforced. Materials were basic. Lessons learned.

Born out of these discoveries was a new awareness of the importance of good grouting procedures, greatly improved grouting materials and vigilant quality control procedures.

Grouts that would not shrink, bleed, separate, and were easy to pump long distances were developed by several major grout manufacturers and are currently used in new construction. The author worked with several manufacturers, testing various formulations, and developed one proprietary grout for his employer.

The American Segmental Bridge Institute (ASBI), Phoenix, AZ developed an ongoing grouting certification program to train and certify bridge grouters as well as educate engineers and inspectors. In addition to new materials, quality control was stressed at all levels. Many bridge, post-tension and engineering companies continue to contribute their time and expertise to make this an ongoing highly successful program. This author graduated in the first class in 2001.

Little formal research has been done in this field of vacuum grouting. To the author's knowledge, only Texas A&M, Austin, TX (Prof. David Trejo, PhD), in conjunction with Texas Department of Transportation, has an ongoing research program into these bridge repairs. Most data has come from the construction companies performing these repairs. Often, this data is shared among field personnel. A technology has been developed.

Precast and prestressed yards can use this technology when inspecting their products. If a void is detected anywhere in the process, a quick repair can be made and the product is saved. Many new post-tension bridge designs and elevated roadways (e.g. Lee Roy Selmon Crosstown Expressway, Tampa, FL) incorporate precast segmental construction for its rapid erection sequence and high quality of materials.

Although voids themselves do not create corrosion, it is the moisture and corrosive environment (salt air) that create this corrosion. As many bridges are over water, repairing voids are a necessity. In arid conditions, this corrosion may be less aggressive.

Why Vacuum Grouting?

In older (generally before 2000) bonded P-T duct construction, neat cement grout was typically used to fill the annular space between the strands and the duct (either plastic or metal). Neat cement grout was the generally accepted method of encapsulation. Cement is an exceptionally good corrosion inhibitor- <u>when</u> in contact with the steel strand. What was not recognized early on was that neat cement grout, in the presence of bare strand, bled excessively. Laboratory and field tests easily show separation of 10 to 15% or more bleed water in a very short period of time, regardless of the quality of grout mixing. As this bleed water evaporates over time the void is created. If the tendon profile is such that the anchorages are at the high-points of the duct, the voids are immediately behind these anchorages. In any environment, and typical of many Florida bridges (over salt water), corrosion can be expected.

Voids can be encountered at different locations along the tendon. On a parking deck, with a multiple draping of tendons spanning many bays, voids can be encountered at the anchorages and at each high point at column locations along the tendons (see case study- Raleigh

Durham Airport Parking Garage). Often, the services of a qualified forensic engineer are required to survey and locate voids.

Blockages in ducts can occur, preventing grout from entering a portion of the duct. An example of this was Edison Bridge, Fort Myers, Florida. The voids were at the bottom of the duct. Construction was post-tensioned concrete I girder. Voids were in 20-30 liter range. Blockages can be caused by crushed ducts or segregated grout as two examples.

In new construction, voids can occur when duct vents are blocked (Benicia-Martinez and Woodrow Wilson Bridges). Congested rebar, aggressive construction, or unaware personnel can crush the vent tubes (often made of plastic). These vent tubes, located at the top of the tendon profile; allow air to escape as the grout is pumped in. No venting equals unsuccessful grouting.

At the Woodrow Wilson Bridge (Virginia), 60 foot reverse profile (anchorages at low points) transverse tendons were installed in the support pylons. The vent tubes had to extend vertically through 14 feet of rebar and concrete before surfacing. The anchorages were about 6 feet below the high point of the tendon. Some of the vent tubes were crushed or buried in concrete. Without the use of vacuum grouting, it would have been impossible to grout these tendons. At Benecia-Martinez Bridge, California, ducted tension bar running vertically through a maze of rebar encountered the similar difficulties.

At all sites, the everyday construction issues arise. Perhaps a broken pump; a grout line gets clogged or snagged on another piece of equipment; or any number of construction site problems can occur and grouting cannot or is not completed. It is here where the specialty grout foreman is called to perform. His or her ingenuity is called into play. Vacuum grouting is just another tool in his gang-box. What makes vacuum grouting so unique is that only one hole is necessary. Often this hole is ½ inch in diameter. Grout must go in, but first the air must be removed. This is the fundamental basis for vacuum grouting. One major advantage of vacuum grouting is the ability to grout through one small hole, without the need for vents.

Understanding Vacuum

There are two fundamental concepts to embrace: **1.** Vacuum does not exist. Even more important: **2.** Vacuum does nothing. Vacuum is merely an expression used to discuss air pressures lower than ambient atmospheric pressure (29.92 inches of Mercury, 14.7 psi, 1 bar, 1014 millibar, 760 Torr, at sea level). Vacuum does not ‘suck’ anything into the void, but rather the air pressure outside this void pushes something towards the void- differential air pressure is doing the work.

Attach a vacuum hose, or draw air out of a water bottle with your mouth. It collapses. What has happened is that you have withdrawn the air from inside the bottle, reducing its internal pressure. External air pressure collapses it. Vacuum does nothing- there is nothing it can do. Visualize a vacuum gauge as reading 14.7psi at the 0” pin and 0 psi at the 30” mark (See Fig.1). This is the reality of vacuum. Vacuum is nothingness.

Def: Vacuum

. pl. **vac·u·ums** or **vac·u·a** (-yo͞o-ə)

1.

a. Absence of matter.

b. A space empty of matter.

c. A space relatively empty of matter.

d. A space in which the pressure is significantly lower than atmospheric pressure

(freedictionary.com)

Fig. 1 Rethink the way you visualize a vacuum gauge

Absolute vacuum can be expressed as 29.92 inches HG, 760 Torr (mm HG), 0 mBar, 0 Bar, -100kpa (all at standard sea level).

Vacuum grouting works because the vacuum pump has removed the internal air from a void, allowing the grout to completely fill that void. This is the entire premise behind vacuum grouting. It is this simple.

Vacuum- Boyle's Law forms the explanation of what occurs in vacuums and partial vacuums:
def:

> 'For a fixed amount of gas kept at a fixed temperature, *P* and *V* are inversely proportional (while one increases, the other decreases).'

Rewritten another way:

> 'For a given mass, at constant temperature, the pressure times the volume is constant'

$$pV=C$$

(National Aeronautics and Space Administration, www.grc.nasa.gov)

For vacuum grouting applications at general atmospheric conditions, if void air pressure is reduced (partial vacuum) to 0.5 Bar, or roughly 15 inches of Mercury, we have removed one half of the air from the void. Remove all the air (0 Bar, or 29.92 inches of Mercury). Air pressure and volume percentages are linear at these pressures.

Demonstrated in the field and represented in the drawings (Fig 2) below is how vacuum grouting works.

In a clear 10 foot PVC pipe, sealed top and bottom, aligned vertically, water at hose bib pressure (50-60 psi, 3.5-4 Bar) is introduced into a valve at the bottom of the pipe. When the air trapped in the tube is compressed by the rising water column to the water pressure of the hose, equilibrium is reached. No more water will enter the tube. We have a partially filled void. Remember the pump-up bottle rockets we used as kids in the Fifties and Sixties? Remove the hose and open the valve- that air pressure is going to shoot the water out.

Evacuate the ten foot PVC, close the valve, and reattach the garden hose. Allow water to fill the pipe. It will fill the pipe virtually 100%. There is no trapped air to reach equilibrium. The minor amount of air trapped at the top is explained. Air is entrapped in the water (it can be seen bubbling out) and absolute vacuum cannot be achieved. The pipe is filled nearly 99.99%. This is the basic principle of vacuum grouting.

One more rule to understand- grout should be pumped. It will not be 'sucked' into the void. Internal friction losses in the grout hose generally will be higher than the 14.7 psi differential air pressure (atmospheric pressure to absolute vacuum). Grout weighs approximately one pound per square inch/vertical foot column. When vacuum grouting overhead or in a vertical column, grout reaches it equilibrium state, assuming zero friction loss in the hose and void, at approximately 14.7 feet.

In very small voids, and using gravity to feed the evacuated void, this suction method can be used, but is time consuming and not efficient from a production standpoint.

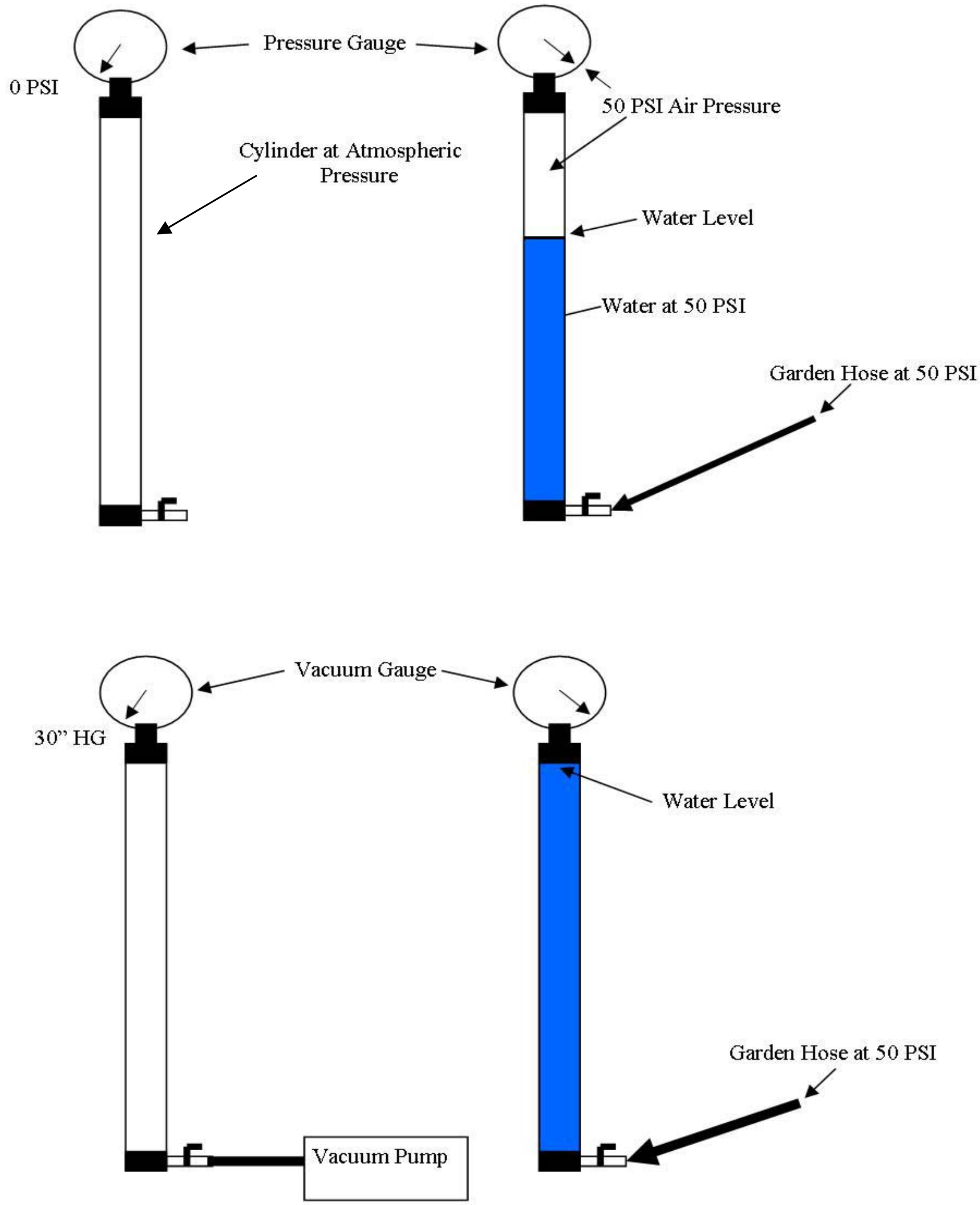

Fig 2 Proof is in this test- 10 foot clear PVC Tube is used to demonstrate the need to evacuate air to fill a void.

The Basic Equipment

There are two primary requirements for vacuum grouting equipment. First is the vacuum pump, the second is the grout mixing and delivery system.

The equipment used for vacuum grouting has improved significantly over the past 7 or 8 years. Initially, some companies used low capacity (low free cfm) diaphragm vacuums (Fig 3). Extremely high, laboratory level vacuum (to the 5 micron) is achieved in the lab, but these pumps are not productive on the job site nor are capable of reducing vacuum to laboratory levels in the field. This author introduced the use of high capacity, refrigeration grade vacuum pumps (Fig 4). High free cfm capacity and exceptionally high vacuum levels (25 micron) could be achieved quickly. This increased job site performance without sacrifice to quality. Adding protective filters and traps to the pump inlet protect the pump mechanism from debris and grit (Fig 6)

Working inside a bridge box culvert, or on the side of a parking structure, requires small mobile equipment. Grouters by nature are a creative bunch. Miniature pumping systems, using compressed air or electricity seem to be a favorite. Commercially available are hand-powered piston pumps, and very small progressive cavity pumps, “baby” Moynos (Fig 5).

Grout mixing has been a challenge. It is generally accepted that the modern post-tensioned grouts perform best when mixed in a high speed-high shear mixer, often referred to as a colloidal mixer. These mixers are generally used on a production job where physical space in not an issue. It is not practical for use inside a box culvert where access is through a manhole or access port 32 inches in diameter. Typical batch size on a vacuum grouting repair is one 50 pound sack of grout material, or enough to fill a 5 gallon bucket. Used in past has been high speed paint mixer attached to large capacity drill. Also used successfully are commercial, restaurant size soup blenders (also called colloidal mixers by the restaurant industry). Self-contained with motor, shaft and high speed mixer blades, these do a very good job. It can be expected each grouter will come up with a suitable mixer. When working outside a structure, or when able to run hoses inside, the larger colloidal mixers have been used. Access to the work usually dictates equipment and methodology.

Fig 3. Diaphragm Vacuum Pump

Fig 4. High Capacity Rotary HVAC Vacuum Pump

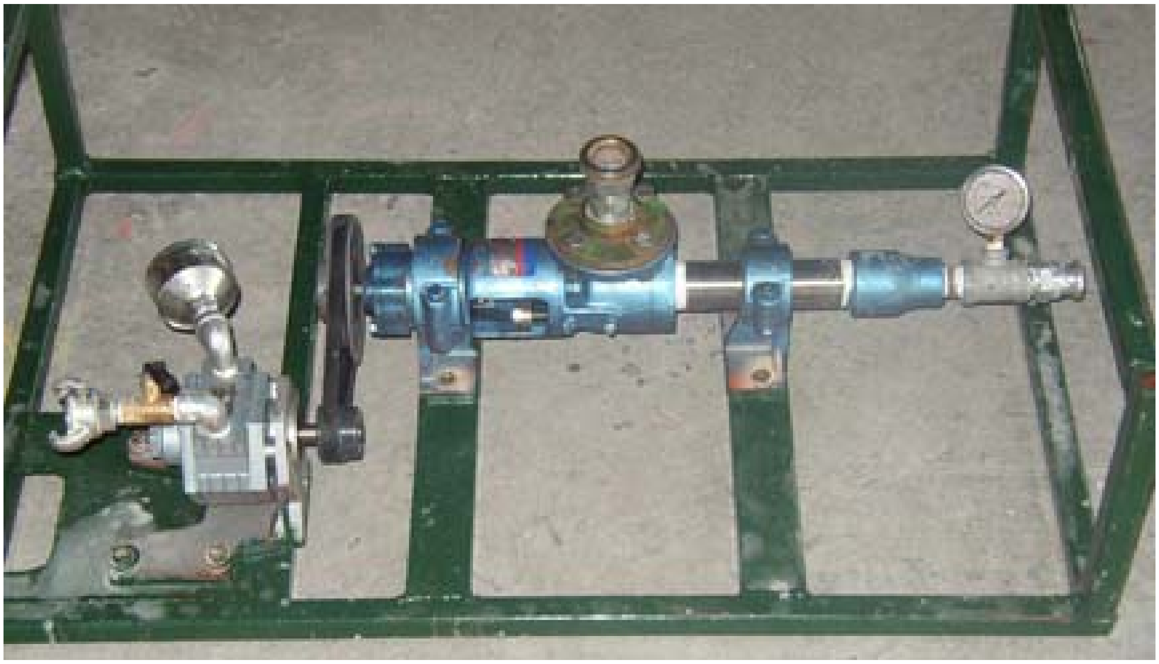

Fig 5 'Baby' Moyno- progressive cavity pump for vacuum grouting repairs

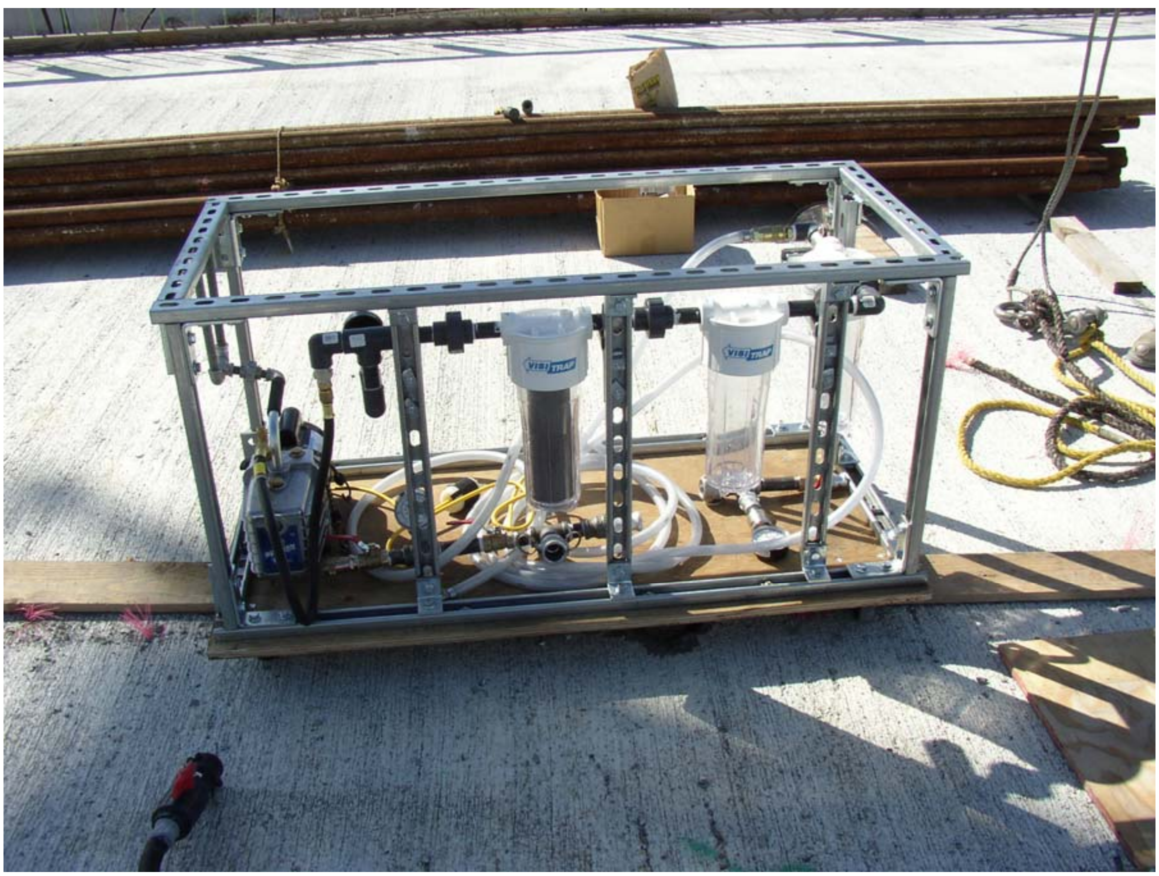

Fig 6 Vacuum pump and protective filters- Benicia-Martinez Bridge, CA

Equipment Advances

Discussed above are the basic tools needed to perform vacuum grouting repairs. Often, additional information is needed. In particular, these questions are asked-'How do I, as an engineer, know how big the void is? Know the void is completely filled?'

The answer is to measure the void. Early void measurement equipment used analog natural gas meters. The void was evacuated and air is allowed to rush back, and the air volume measured. There were variations on this methodology. This equipment was bulky, heavy, slow, and not as accurate as newer electronic equipment (Fig 8). However, the limitations of both types of systems are discussed below.

More modern equipment uses mass flow technology, calibrated for air or nitrogen mass. It has been used in several variations- measuring air being withdrawn from the void; measuring air rushing back into an evacuated void; or pressurizing the void. All use Boyle's Law- for a given volume, doubling the pressure (from 1 bar to 2 bar) is adding one volume; removing one volume equals one volume, as examples.

Once the void size is determined, grout can be measured as it is pumped into the void. This can be done by measuring the volume drop in the grout tank, or using an electronic grout flow meter (Fig 9).

There are limitations of void measuring equipment (VME) regardless of technology used. VME will measure the entire void, just not what is visible in the borescope. In a typical longitudinal external tendon, voids can exist at each end of the tendon; connected by a bleed track, all will be measured. (See Garcon Point Bridge and Raleigh Durham Parking Garage case studies).

A test cylinder (Fig 7) should be on site, either provided by the state DOT, engineer or contractor to demonstrate the accuracy of the void measuring equipment. Repeatability, the quality that results measured will be consistent, is of primary importance.

Fig 7 21.7 Liter Calibration Cylinder for Void Measuring Equipment (VME)

Fig 8. Forensic Void Measuring Equipment- contains system for pressurizing and detecting leaks

Fig 9. Grout Flow Meter- measures in liters or other standard units

Measuring voids has been a real challenge at many sites because of the disparity between air measurement and grout pumped. The engineer/inspector and contractor must understand these limitations when performing repairs. Volume measuring equipment seen here requires the void to be airtight. Leaks will distort the volume measurements. One company has equipment that is said to compensate for leaks. The author has not seen this in operation.

Challenges of Vacuum Grouting

For most-effective vacuum grouting to be performed, it is imperative that air leaks be sealed. Approximately 75-90% of the time required for proper vacuum grouting repairs is devoted to finding and sealing air leaks. Once a void is airtight, vacuum grouting is a very quick repair.

Air leaks can be as small as a pinhole, or considerably larger- a broken duct, loose transition collar, loose or ill-fitting grout cap, spiral wound metal duct in poorly consolidated concrete are examples.

Fig 10. Pressurized Duct with Soapy Water Identifying a Leak- Sunshine Skyway Bridge, Tampa, FL

Chasing and repairing leaks is time consuming. The methodology, however, has stood the test of time. A mixture of liquid soap and water in a spray bottle, along with compressed air into the void is perhaps the simplest and most effective method of leak detection (Fig 10). Knowledge of the post-tension duct system, internal or external, helps in predicting the likely locations for air leaks. Once the air leaks are fixed, vacuum grouting can commence.

In a project where many voids need to be repaired, a crew of two can prepare the entire project, locating and repairing leaks, before the grouting crew arrives. Small voids, typical at many anchorages, take less than 10 minutes to vacuum grout. Usually it takes more time moving around inside of a bridge box culvert and setting up than the grouting itself.

Small air leaks are ever-present. Using Boyle's Law, partial vacuum grouting performance can be estimated. Upon drawing as complete a vacuum as possible, the inlet valve is closed and vacuum pump is disengaged. Measuring the vacuum loss over time is judged over the time estimated to pump grout. If it takes 5 minutes to lose 3 inches of Mercury, and 5 minutes to pump the grout, it can be predicted that approximately 10% of the void will have air. It is generally not a good idea to over-pressurize the grout. 30 psi is good point to stop grouting. Boyle's Law says the air will be compressed to 2 Bar (30 psi), so the remaining void volume is now 5%. If this is acceptable to the engineer, then grouting could continue. It is also impossible to predict the location of the leak, so it cannot be expected this air will bleed out of the duct or void or will be blocked by the inflowing grout.

Vacuum grout materials are the same as used in production grouting. Most post-tensioned grouts are packaged in 50 pound bags, suitable for repair jobs.

Some Representative Projects:

1. Woodrow Wilson Bridge, Virginia: New construction - internal duct

Vent tubes in some of the transverse tendons located in the approach pylons were crushed during the concrete pours. These vent tubes were located at the top of the plastic duct, approximately 14 feet below the surface of the concrete. The anchorages were about 20 feet in the air and had to be accessed by manlift. It was impossible to drill into the duct to provide ducting of the grout. Grout volume required was determined mathematically (volume of duct less volume of strand). Estimated volume was 60 liters. After the anchorage grout caps were leak-tested and sealed, grout was mixed in the general contractor's large colloidal plant. The duct was evacuated using a large capacity refrigeration vacuum pump. The grout was introduced and pumped quickly until the estimated volume was nearly reached and pumping was slowed. As pressure started to build, as measured at the grout cap, grouting was completed. A volume check at the pump indicated filling of over 95% of the estimated void.

2. Raleigh Durham Parking Garage, North Carolina: Existing construction- internal ducts

The parking garage at Raleigh Durham Airport was undergoing a major expansion. The original garage construction included extensive post-tensioned construction. Horizontal tendons spanned 100’s of feet and many bays. Prior to construction of the expansion, the engineering firm of Wiss, Jenney, Elstner supervised inspection of the tendon anchorages in the older section. Approximately 60% of the investigated anchorages had voids. Electronic void measuring equipment was first utilized on this project and demonstrated the limitations of such equipment. The RDU Airport Authority was wise to investigate their structure at this point as anchorages were accessible, saving time and money if performed at a later date.

The electronic void measuring equipment measured the entire void- from one end of the tendon to the other. Air will travel through a water bleed track, but grout will not. Inspections of the voids using a borescope gave estimated volumes at the anchorages. Pumped grout, measured using an electronic grout flow meter, matched the estimated anchorage void volume. Additional grout pumped in each high point along the tendon started reaching the volume measured with the electronic equipment.

3. Garcon Point Bridge, Pensacola Florida- Existing construction- external ducts

Demonstrated at this bridge was the issue of volumetric measuring of voids. Voids were present at both ends of the external longitudinal tendon. A simple hammer tap indicated a continuous water bleed track from one end of the tendon to the other. These voids were interconnected. The void measuring equipment again measured the entire void.

Vacuum Assisted Grouting

This method of grouting utilizes the advantage of a vacuum pump located at the far end of a tendon. Grout is introduced at one end while vacuum is drawn from the other. The net improvement of grout pumping pressure is 14.7 psi. The advantage is that air is removed from possible high points in the duct and from the interstitial spaces of the strand. A high capacity vacuum pump should be used to keep the vacuum high as the grout is advancing. A trap is necessary to prevent grout from entering the vacuum pump (Fig 6). Vacuum assisted grouting was used at the first Sunshine Skyway Repair project. The damaged loops tendons were replaced with conventional mass concrete/rebar below the water table, and stressed bar in the upper sections. The last 10 feet of the stressed bar used vacuum-assisted grouting to ensure complete encapsulation of the bar (Fig 11).

Photo Courtesy of Euclid Chemical

Fig 11. Cutaway of Sunshine Skyway test sample, loop tendon repair

Training (Education)

Education of field personnel in the reasons, technologies and procedures of vacuum grouting can easily be completed in two or three days, including time to assemble the necessary equipment, some classroom time, and run simulated or real repairs.

Summary

Vacuum Grouting has become a necessity for the contractor involved in bonded post-tension construction. Be it repairs of existing structures, or new construction, having skilled personnel and proper equipment can save the contractor valuable time during construction. The basic equipment and some education are inexpensive, and will save the contractor substantially more money if his grout foreman can complete these repairs in a timely fashion. Although not a cure-all for poor construction techniques, or construction issues, vacuum grouting needs to be in the foreman's toolbox.