Technology for the People Initiative

Working Paper

Smart-Phone Based Construction Monitoring

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The Case for Smart-Phone Based Construction Monitoring

Poor governance in construction of public facilities, like schools, roads, or health units, is a considerable development concern. Construction is a major sector in terms of financial outlay of a district government, and is responsible for the development of infrastructure capital that is central to growth, citizen services and improved quality of life. Low quality construction compromises service delivery to citizens, which ultimately leads to erosion of the writ of the state. Therefore, monitoring of construction projects, to ensure that the work done is up to the requisite quality level, is an important governance task.

Small-scale construction projects, especially in remote and rural areas, are often executed by local contractors (*thekedars*), who have been trained through apprenticeship and who have not studied civil engineering formally. Therefore, adherence to construction standards is often a major issue, and needs active monitoring at all stages of the project. Moreover, corruption in such projects appears to be rampant, according to anecdotal evidence collected from the field. There are frequent reports of government officials actively colluding with the contractors to get a portion of the share of the contract, in exchange for lax monitoring and giving a free hand to the contractor.

Monitoring a multitude of projects through site visits is not a simple task. When a government engineer visits a construction site, the risk of the monitor himself being involved in the collusive corruption network cannot be overruled. Moreover, whether the monitor physically visits the site in a remote area, or simply fills a report without traveling a large distance, itself is a concern. Even when a visit has been executed, the monitor's findings and observations are not verifiable by higher officials, and hence, it is difficult to hold the monitor accountable for his fieldwork. With multiple simultaneous projects being executed in any given district spread over a large geographic area, adequate monitoring construction projects to ensure adherence to quality standards and to minimize chance for corruption is by no means a simple undertaking.

In this study, we explore the possibility of using low-cost cameras and smart phones for the monitoring of small-scale construction projects that are typically undertaken in rural and semi-rural areas. Our focus is on projects that are of high frequency and executed by mid or low-level contractors. Such projects include government buildings of a few rooms (such as schools or rural health units) and small farm-to-market roads. These kinds of projects are the ones that are less likely to be adequately monitored, and have the most risk of suffering from poor quality and corruption. Larger projects have higher visibility and a different economic and political context and auditing these will require a more complex approach.

There is no shortage of standardized quality testing procedures in civil engineering practice. However, many such procedures require lab testing, or expensive field equipment, and are therefore, not deployed for the type of small-scale projects that we target in our study.

We explore the possibility of using a smart phone as the primary tool in the monitor's tool kit during field visits. The key idea is that the monitor will take photographs of critical construction steps and materials in a pre-specified way, according to a standard protocol for each step of the monitoring process. These photographs will be transmitted to a central monitoring office at the provincial level, where trained civil engineers will review them and record their observations on the quality of the construction work at the site. The financial payments to the contractor can be linked to this report; unless the review cell approves a construction stage, the payment for the next stage may not be released.

The proposition is attractive in several respects. The visit itself and its timing can be verified immediately by the monitor's higher-ups through GPS tracking on the device. The images taken on the phone can provide much better logging of monitor's observations than the current practice of filling out text-based visit reports, and these observations are now verifiable at a later stage. In the provincial review cell, much more qualified and experienced resources can be employed, because they will not have to conduct field visits and can therefore monitor a large number of projects simultaneously.

However, the most significant advantage of this approach is that the visits of the monitor will now be mostly decoupled from the actual reporting and accountability of the contractor. The field monitor now simply acts as the eyes of the qualified engineers sitting in the provincial review cell. Because of the large distance between the review engineers and the actual construction site, the possibility of collusive corruption can be minimized, and the monitoring tasks can be better standardized across the province.

Not all quality testing procedures can be carried out through camera images. Some tests require lab testing of material or expensive equipment. However, our observation is that most small-scale projects do not employ such testing procedures to begin with. Most existing quality testing procedures that are actually deployed for such projects are based on physical observations at the site by the monitor. Therefore, replacing those field observations by images appears to be a feasible idea in the context of small-scale projects in rural areas. Our approach is not of developing foolproof testing procedures – rather we ask the question of how much pilferage and corruption can be blocked through the use of cameras?

There are certain sensors, other than cameras, that would be useful in determining construction quality. For instance, a Ground Penetrating Radar (GPR) is often used in road quality inspection in developed countries. The reflected radar signals are different for various sub-surface structures, and the thickness of construction layers can be inferred from it. Similarly, there are sensors that can assess concrete strength, or determine the thickness of steel bars embedded in a structure. Deploying these sensors in the field is expensive and not feasible in the context of dispersed small-scale projects in rural areas.

Several research groups in recent years have focused their attention on image-based construction monitoring, mostly in the context of automated image analysis. These approaches aim to acquire a 3D point-cloud of the construction site or its sub-portions, and then compare the as-planned model with the as-built scans. We conclude that automation of verification using images of some tests under lab conditions is possible but, as yet, these approaches do not generalize well to field conditions. This position is supported by the findings of Lee et al. (2011) who developed a vision-based system to evaluate rust on bridges but found that there are significant challenges for such a system to perform well in field conditions. A more detailed review of experimental approaches for camera-based construction monitoring is given in the appendix at the end of this paper.

In contrast to these computationally expensive automated image analysis approaches, our approach is practical because of its simplicity. We are not recommending the use of image processing techniques to extract point-clouds or to make automated assessments of construction quality. Rather, our focus is on collecting appropriate photographs, according to standardized protocols, that can be manually interpreted by experienced civil engineers at a central review location within the province. This approach side-steps many computational and implementation difficulties that require significant computer vision and image processing expertise, and yield simple tests that can be executed in the field even by non-engineers.

Before we discuss the various image-based quality monitoring tests, it is important to review the process and stages of construction, because our proposed testing strategy will be embedded in different stages of construction.

Process of Construction

In this study, we consider construction projects that are small-scale and away from the major cities. These are the projects that are mostly likely to be neglected in terms of their monitoring requirements. It is unlikely that expensive testing equipment will be deployed for these projects. These projects are typically contracted to low-level *thekedars* who do not employ civil engineers for quality control. Anecdotal evidence suggests that corruption is a major issue in such construction projects. We have concentrated on two types of such projects: small road construction and small-scale building projects.

Construction projects in the government are initiated after a need has been identified and brought to the attention of the relevant department. Once projects have been identified, feasibility and estimates are made. After this step, the project is designed, tenders are issued, contractors selected and finally the project is executed. Bids from different contractors are compared with each other and to the Market Rate Schedule maintained by the Ministry of Finance. This schedule has prices for both materials and also aggregate rates per foot, area or volume of common types of construction. It is updated quarterly and adjustments are made to payments if prices of construction materials or manpower change during construction. These adjustments are called price variations. Special provisions are made for items not in the Market Rate System.

Private contractors carry out the actual construction while government departments are responsible for project selection, design and monitoring of execution. Specifically monitoring is the responsibility of engineers in the government. The official responsibility for government projects in a district lies with an Executive Engineer (XEn), followed by a Sub-Divisional Officer (SDO) and a Sub Engineer, who supervise smaller geographical areas. This is a common hierarchy in departments that carry out construction.

There is no formal monitoring procedure for quality involving instruments such as checklists within the district government. One of the monitoring activities that is carried out with consistency is checking the progress of construction sites to ensure that funds are disbursed as specified in the schedule. In the absence of an explicit mechanism to verify quality, it is assumed that construction has been carried out according to specifications, unless the supervising engineers raise objections. This is why if an investigation or legal action is carried out, it most often implicates both government engineers and the contractor. Monitoring for quality of construction is ad-hoc and is left up to the administration's discretion.

An approximate breakdown of the costs involved in construction of buildings and roads projects is given below. Note that material makes up the bulk of the cost of projects in both cases.

	Materials	Equipment	Labor	Other*
Buildings	60%	5%	15%	20%
Roads	45%	25%	10%	20%

*Other costs include financing and administration expenses

Corruption in Construction

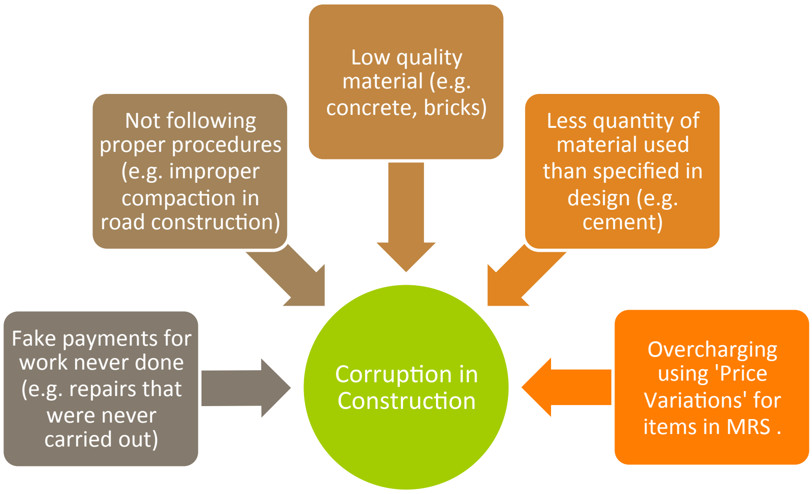


Figure 1. Major sources of corruption in construction.

Price Variations
Price variations are a major source of corruption carried out in collusion with government officials. The favored contractor puts in a low bid allowing him to win the contract. Later the contractor is compensated for the initial low bid by getting price variation orders in his favor allowing him to charge more than what he bid.

Since a formal study of corruption is not part of this study, the information presented in this section is anecdotal in nature.

Parts of the construction that cannot be easily checked after construction has been completed are prime targets for corruption for contractors. Examples of these would be the type of aggregate stones used in roads, bricks and steel used in buildings.

We visited many sites as part of this project to collect pictures and understand the impact of corruption on construction. Following are some anecdotes from our field visits.

At one of the sites the concrete for the damp proof course had not been prepared properly and so did not give a uniform appearance. This defect can have severe implications later on in the life of the building. Without proper application of the damp proof course moisture in the ground travels up into the walls of the building ultimately weakening the brickwork.

While visiting another site the civil engineer accompanying us noted that the Plain Cement Concrete being used had not been mixed properly and the mix that had been prepared had debris in it. These were projects being built in the heart of the city close to where top district officials sit. In our visits we noted that as we moved away from the city centers the quality of construction decreases.

Officials at an anti-corruption agency told us about corruption in a major road project relating to inferior stones used for a layer of the road. Since transportation forms a large part of the cost of the stones, they were sourced from a nearby hill instead of from the hills specified in the contract, whose stones are known to be of the strength and shape required for road construction. This resulted in a weak base layer and ruts started developing when heavy loads started passing over the road since the stones used were not of the right shape and strength to bear these loads. The difference in rocks between these two hills can be easily verified and would have been apparent to government engineers but strong political connections allowed the contractor to get away with this violation.

We also noted that monitoring engineers were sometimes out of touch with construction projects that were farther away from their office. In one instance when visiting a building under construction, the engineers forgot the way to the site, indicating that they had not visited the site regularly, even though it had been under construction for months. This implies that the contractor had been given a free hand to do as he pleased at the site.

Image-Based Construction Monitoring System

A system to monitor construction will consist of field monitors who will visit construction sites and use smartphones or DSLR cameras to collect pictures from the field according to pre-defined protocols. The pictures will be time and geo-tagged by the smartphone or DSLR. These will then be uploaded to a provincial construction-monitoring server to be reviewed by experienced engineers or auditors, who will provide their feedback on the quality of construction.

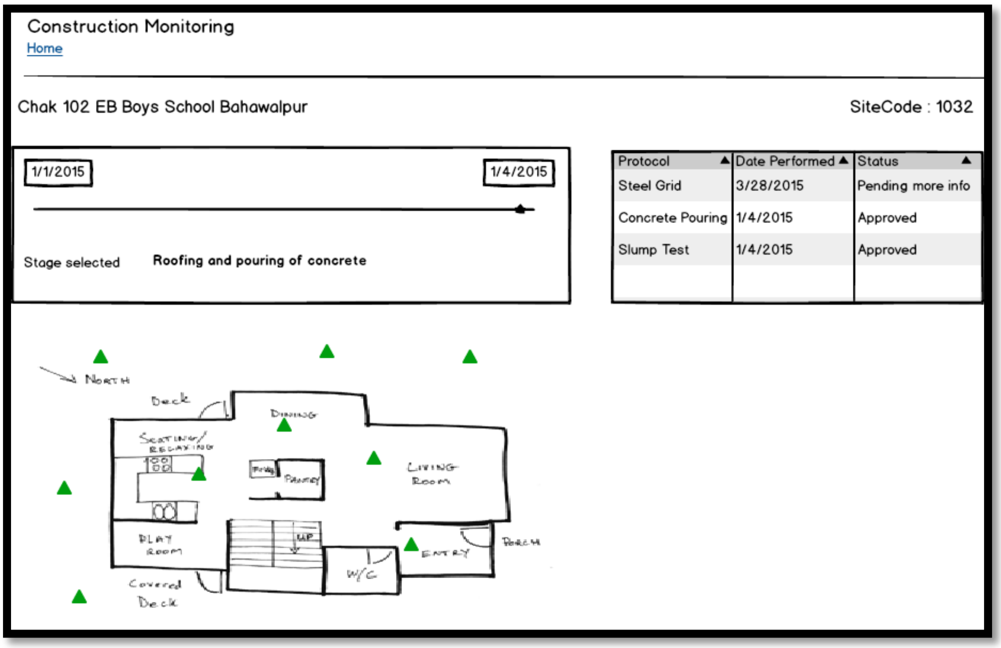
This approach geographically separates part of the monitoring process from the site of construction. This is an important feature of the system since most corruption in construction occurs in collusion with local government monitors. This monitoring system should be implemented in a way so as to keep the contact between the local and remote officials as minimal as possible.

At each stage of construction, the auditor will be presented with pictures or videos of a site taken by the monitor. The auditor will then take one of three actions for each of these pictures: 1) The auditor may mark the quality of construction as being satisfactory, 2) the auditor may mark the construction as being deficient in quality, or 3) the auditor may request additional pictures to be able to make a decision.

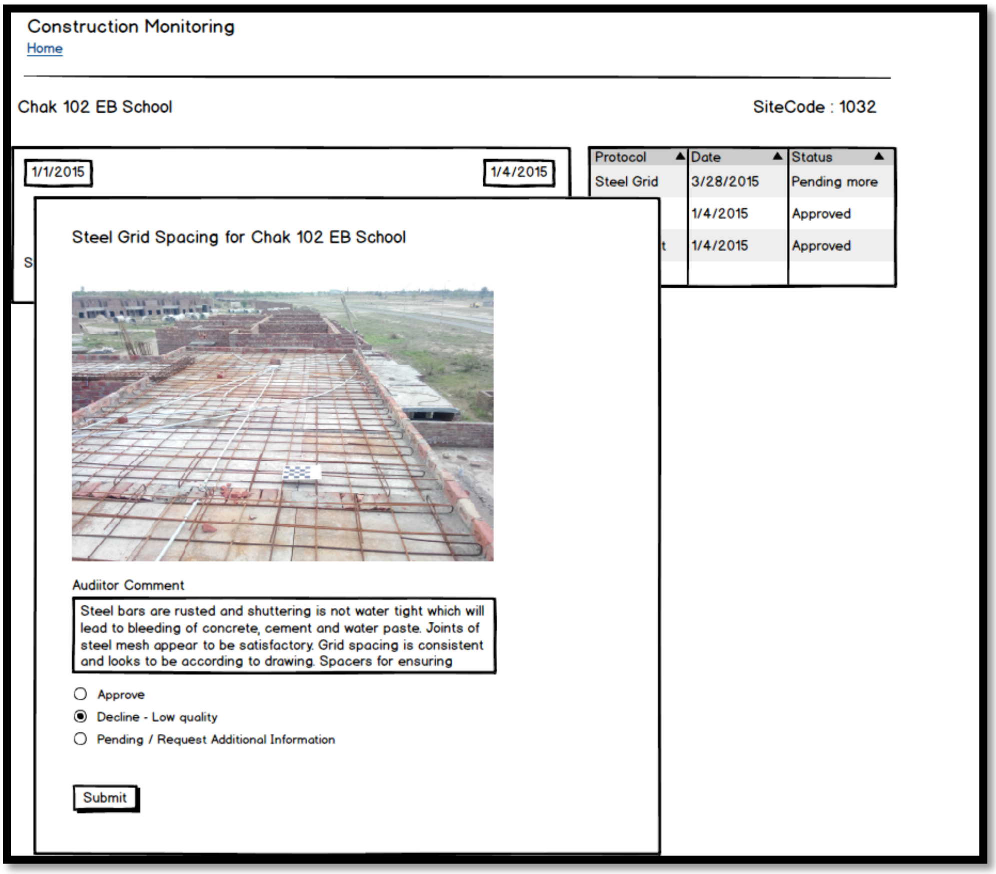
If the quality is satisfactory then no further action needs to be taken and the protocol and stage of construction will be marked as being approved. If the quality is found to be deficient, this will be communicated to the local authorities responsible for monitoring the construction along with the comments of the auditor.

In cases where the photos are unclear or have not have been taken according to protocols, the auditor may request the monitor to take additional or more detailed pictures. He will communicate the kind of picture that he wants which will be forwarded to the monitor for further action.

The following figures outline the main functionality of the system for the auditor. The auditor will be presented with a timeline that can be used to browse the site temporally. Once the auditor has set the stage that she wants to review, the stage of construction appears, along with 1) the points on the plan where pictures are available (these are shown in green) at that time and 2) the protocols that are available for this stage of construction.



Clicking on the protocols will open a window with details of that protocol, as shown in the figure below. The auditor will then write their comments on the protocol, have the choice to either accept the results of the protocol, to decline it due to quality issues or to request further pictures or information.



Stages of Construction and Monitoring

We now discuss the stages of construction, and their monitoring strategies in detail. We studied two types of construction as part of this project, small roads and buildings. For each of these we have provided a table that lists the stages of construction and for each stage the sources of corruption and possible solutions.

Roads

Typically small road projects are those that are less than 50km in length. A typical small contractor may take about a year to complete such a project. In these roads coarser aggregate (*geara*) is used, and low quality compaction is employed. Instead of asphalt, TST (triple surface treatment) is typically used, because it is more economical. It is locally called '*luk*' and is heated on-site in drums. Pre-mixed asphalt is much more expensive because it is treated in an asphalt preparation plant, and is used only in larger projects such as highways or motorways.

Construction on a road proceeds in what is known as 'reaches'. A reach is a small stretch of road on which work is carried out at one time. A reach may typically be 500 to 1000 feet long, but can vary from project to project, depending on the capacity of the contractor to simultaneously deploy resources.

The major stages of road construction are as follows:

1. Sub-Grade Preparation: The site is prepared through leveling and a base level is reached by filling with soil of a certain specified quality. This soil is then compacted through a sheep-foot roller.

2. Sub-Base: The first layer, called sub-base, is laid. Sub-grade is composed of crushed stones (*bajri*) which is compacted by a roller.

3. Base: The next layer is that of base, which also consists of crushed stones (*bajri*) but of a larger size than that of the sub-base. Stone dust is filled within the gaps of these stones. This layer also needs to be compacted by a roller.

4. Priming: To prepare for asphalt laying and to ensure that it binds well with the base layers, a mixture of kerosene and bitumen is sprayed on the site.

5. Asphalt or TST: Asphalt layer is paved onto the site and is compacted by rollers. For smaller less-expensive projects, Triple Surface Treatment (TST) is used instead of asphalt.

In the following table, we describe the details of each stage, along with the questions that are relevant from monitoring point of view, how the contractor may try to save money by compromising quality at each stage, and finally, what imaging protocol may identify the short-comings of the construction at that stage.

Step 1: Sub-Grade Preparation	Questions to Ask	Sources of Corruption	Possible Imaging Solutions
Survey of site to determine the depth of filling required to get to base-level. Base level is higher than the surroundings, to not allow water to retain. Survey is done by government agency awarding the contract.	Is survey correct?	Even though government departments conduct the survey, it is known that the office awarding the contract may collude with the contractor to report a lower surface level. This helps the contractor because he can charge substantially more material cost for filling material needed to reach base-level.	May not be possible to curb this through imaging, but later core extraction test can show results. This is also a hard area for existing monitoring mechanisms.
Issues in delivery	How much material (say A4 soil) is delivered at site?	Guard deployed at site may be asked to over count the deliveries. It is also reported that sometimes, volume of a trolley is reduced by having planks arranged at the bottom of the trolley.	May not be possible to curb this through imaging Dumped piles may be photographed, but this is a very frequent activity, and hence covering it completely will require a monitor to be continuously present at the site, which is infeasible.
Ploughing the site (so that when watered, compaction is better)	Does not need to be monitored		
Water sprinkling to OMC level (optimum moisture content), established by soil testing lab, typically 10% to 15%).	Does not need to be monitored..	One can probably do lesser passes, to save diesel cost.	
Compaction runs (through sheep foot roller). At this step, the sub-grade preparation of existing soil is complete.	Does not need to be monitored.		
Dump and spread A4 soil (mud) in 9 inch cycles, compressed to 6 inches, so that compaction is optimal. There can be *n* such iterations. Each layer will require steps of dumping, grading, moisture content and rolling for compaction.	Is the compaction sufficient? Is the soil of appropriate grade? Soil should be free of vegetation, of appropriate grade, should be free from sand and slit (only clay).	Contractor may only compact the top layer, or compact multiple layers at one time rather than doing 9 inch cycles, to save diesel and equipment rental. Cheaper soil from nearby sources may be used.	Soil dumps may be randomly photographed at successive zoom levels. Testing compaction is not easy. Theoretically, the sample is put in oven and loss of volume is measured. A coarse test, often deployed by site engineers, is to impact the surface through an object or heel of foot, and then photograph the impression. This can be done with successive layers of compaction.

Step 2: Laying of Sub Base	Questions to Ask	Sources of Corruption	Possible Imaging Solutions
Dumping, grading and compaction of sub-base material, which is crushed stones of relatively smaller size (1.5 – 2 inches). The thickness, compaction and the gradation of aggregate is specified in contract. Generally 98% compaction is required, which means that the loose air content should be reduced to 2% only. The compaction layers may be multiple, depending on the thickness of this layer.	Is the sub-base layer of appropriate thickness ? What is the source and quality aggregate? Shape of aggregate should not be elongated but should be mostly round. Stone should be of appropriate hardness. Is the compaction appropriate?	Contractor may mix stones of good hardness with softer stones which are cheaper. Contractors also source stones from nearby quarries whose stones are cheaper. Compaction may not be appropriate.	Taking image of road after compaction is completed Taking photos of aggregate dumps. Aggregate dumps of photos should be taken with scale. Compaction can be tested using the 'heel test' mentioned above.
Step 3: Laying of Base	**Questions to Ask**	**Sources of Corruption**	**Possible Imaging Solutions**
Dumping, grading and compaction of base material, which is crushed stones of larger size than the sub-base (3.5 – 4 inches) and a fine material that fills the voids between the stones known as stonedust. First crushed stones are dumped, graded and a first pass of compaction is done. Then on top of this stone dust is dumped, graded and then compacted. After all layers are compacted excess stone dust is removed from the surface by cleaning manually or with mechanical brushes. The above process may be repeated multiple times depending upon the required thickness of this layer.	What is the source and quality of aggregate? Shape should not be elongated but should be mostly round. Stone should be of appropriate hardness. Is the stone dust of appropriate quality? Stone dust should have an equal ratio of coarse and fine particles. Is the top layer of base clear of stone dust? Stones should be visible and should appear 'keyed' in the road. Is the base layer of appropriate thickness?	Contractors may source material from quarries whose stones are cheaper and not of appropriate quality. Contractors may use stone dust of lower quality. Cost of stone dust drops if only one of coarse or fine particles are used. Compaction may not be appropriate. Contractors may not clear the top layer of stone dust to save on labor costs and time. Contractors may construct a thinner base layer to save costs.	Throwing a handful of stone dust in the air and taking video of it can tell the quality of the stone dust. Half of the mass of the stone dust should return to the hand. Taking photos of stone dust and aggregate dumps. Aggregate dumps of photos should be taken with scale as mentioned in the test above. Taking image of road after compaction is complete. Test compaction with the 'heel test' as in described above. Taking images of the road to assess if excess stone dust has been wiped off. Thickness of this layer can be determined using the road layers test described in the protocols section.

Step 4: Priming	Questions to Ask	Sources of Corruption	Possible Imaging Solutions
A mixture of kerosene and bitumen (40% kerosene and 60% bitumen) is prepared on site. This mixture is heated and then sprinkled (0.6 – 1.6 liter / sq. m) onto the base layer.	Is sufficient quantity of mix sprayed per sq. m? Is the ratio of bitumen to kerosene appropriate? Bitumen used should be of appropriate quality. Is the prime coat spread evenly over the road?	Contractor may use cheaper bitumen e.g. field reports tell us that bitumen smuggled from Iran is of lower quality than that produced by the refineries. Contractor may use less quantity of bitumen per sq. meter Contractor may not spread prime coat evenly due to carelessness.	Assessing bitumen quality and mix is not possible visually. Taking images of receipts issued by refineries upon purchase of bitumen to confirm that it has been purchased from an approved refinery (e.g. Attock Refinery or National Refinery Limited) Taking pictures to assess if prime coat is spread evenly over the surface
Step 5 i): Asphalt Laying	**Questions to Ask**	**Sources of Corruption**	**Possible Imaging Solutions**
Asphalt arrives in dumpers on site and is fed into a paver. The paver lays the asphalt onto the road to the desired thickness after which the asphalt is compacted by rollers.	Is the asphalt of appropriate quality? Is the thickness of asphalt layer as per specifications? Is the temperature of asphalt appropriate?	Contractor may use asphalt with lower bitumen content since bitumen is an expensive material. Contractor may lay a thinner layer of asphalt to save on quantity of asphalt.	It is not possible to judge quality of asphalt visually. Taking images of receipts issued by batching plants upon purchase of asphalt. Thickness of asphalt layer can be assessed from performing the road layer test described in the protocols section.
Step 5 ii) Triple Surface Treatment	**Questions to Ask**	**Sources of Corruption**	**Possible Imaging Solutions**
Triple surface treatment (TST) is frequently used as a cheaper alternative for pre-mixed asphalt described above. Its cost is almost half that of pre-mixed asphalt. This type of road surface is composed of three layers each of which has a different size aggregate bound together by bitumen. First the aggregate is dumped and graded on the road after which it is sprayed with bitumen and compacted. This is done for each for each of the three layers of aggregate.	Is an appropriate amount of bitumen used per sq. m? Is bitumen quality satisfactory?	Contractor may spread a thinner layer of bitumen. Contractor may use bitumen of lower quality.	The thickness of the layer of bitumen used can be coarsely assessed using the road layers test described in the protocols section. Bitumen quality cannot be assessed visually. A lab test known as the penetration test is used to assess bitumen quality.

Monitoring Protocols for Roads

Based on the understanding of road construction stages and the potential sources of corruption in their construction described above, we propose a set of testing protocols based on imaging through cameras. These protocols are summarized in the following table, organized by their stages of construction. Note that roads are made in units known as reaches. These are typical 500 – 1000 ft in length. Work is done one reach at a time.

Stage	Testing Protocol	Reason for Test	Time for Test
Subgrade preparation	Picture of soil dumps	Quality of soil	When material arrives or at time of dumping
	Picture with camera close to the road	Quality of workmanship	At completion of base
	Picture of road while standing up	Overview / Orientation	At completion of base
	Video of heel test	Compaction	At completion of base
Sub-base	Picture of aggregate dumps with measure	Quality of aggregate	At start of every reach
	Picture with camera close to the road	Smoothness and clear from shrubs and debris	At completion
	Video of heel test	Compaction	At completion
	Picture while standing up	General quality of road	At completion
Base	Picture of aggregate dumps with measure	Quality of aggregate	At start of each reach
	Picture with camera close to the road	Smoothness and clear from shrubs and debris	At completion of each reach
	Picture of stone dust dumps	Quality of stone dust	At start of each reach
	Picture with camera close to the road	Smoothness and clear from shrubs and debris	At completion of each reach
	Video of heel test	Compaction	At completion of each reach
	Picture while standing up	General quality of road	At completion of each reach
Priming	Picture of road while standing up	Evenness of bitumen, kerosene mixture spray, road clear from dirt	At completion of each reach
	Picture of bitumen receipt	Source of bitumen	
Triple Surface Treatment	Picture of bitumen receipt	Source of bitumen	
	Picture with camera close to the road	Quality of aggregate and bitumen spreading	Randomly while a reach is at this stage
Asphalt	Picture of asphalt receipt	Source of asphalt	
	Picture with camera close to the road	Quality of workmanship and technique during asphalt laying	Randomly while a reach is at this stage
Road completion	Road layers test (for description, see next section)	Thickness of each layer/ quality of material used	Every 5 km

The testing protocols described above are simple to execute, and do not necessarily have to be performed by a civil engineer. Instead, any appropriate staff member with some training in appropriate protocols for photography can potentially execute these testing protocols. Once the images or videos are transmitted to the central review location, experienced civil engineers can give their input.

We discuss examples of some tests in some detail below, including comments by our consultant civil engineer about observations that can be made from these images.

Pictures of Material Dumps at the Site

1. Picture of soil used for filling as subgrade material.

Consultant Engineer's comments: Soil appears to be of excellent quality – this soil is probably A4 grade, which is ideal for preparation of the subgrade. It appears free of sand and silt and appears only to have clay in it, which is good.

2. Picture of aggregate dump

   Example picture of an aggregate dump is shown below, taken at a construction site. It would be recommended to use a measuring scale within the picture.

Consultant Engineers comments:
These stones for the sub-base are of very high quality, they are round and not oblong.

3. Picture of sub-base while standing up and close to the ground

Consultant Engineers comments:
These pictures show that aggregate is mixed with crushed stone which will lead to poor bonding. It also seems like sand has been mixed with the stone dust. There is a lot of loose material and it appears that the road was not compacted properly. Overall the quality of this construction is poor.

4. Picture of aggregate used for Base.

Consultant Engineer's comments:
These stones for the base are of very high quality. They are round, not oblong, and do not appear to be sandy or flaky.

Video Tests for Assessment of Compaction and Quality

5. Heel Test Video

The Heel Test is an informal testing mechanism employed by field engineers to test compaction of a surface. The engineer moves his weight on the heel of this shoe in an attempt to dig it into the surface. Then the impression on the surface is viewed to judge the level of compaction. This type of test is easy to conduct on video. In this video a person should press the surface of the road with his heel and the video should then zoom into the impression.

6. Video of stone-dust test

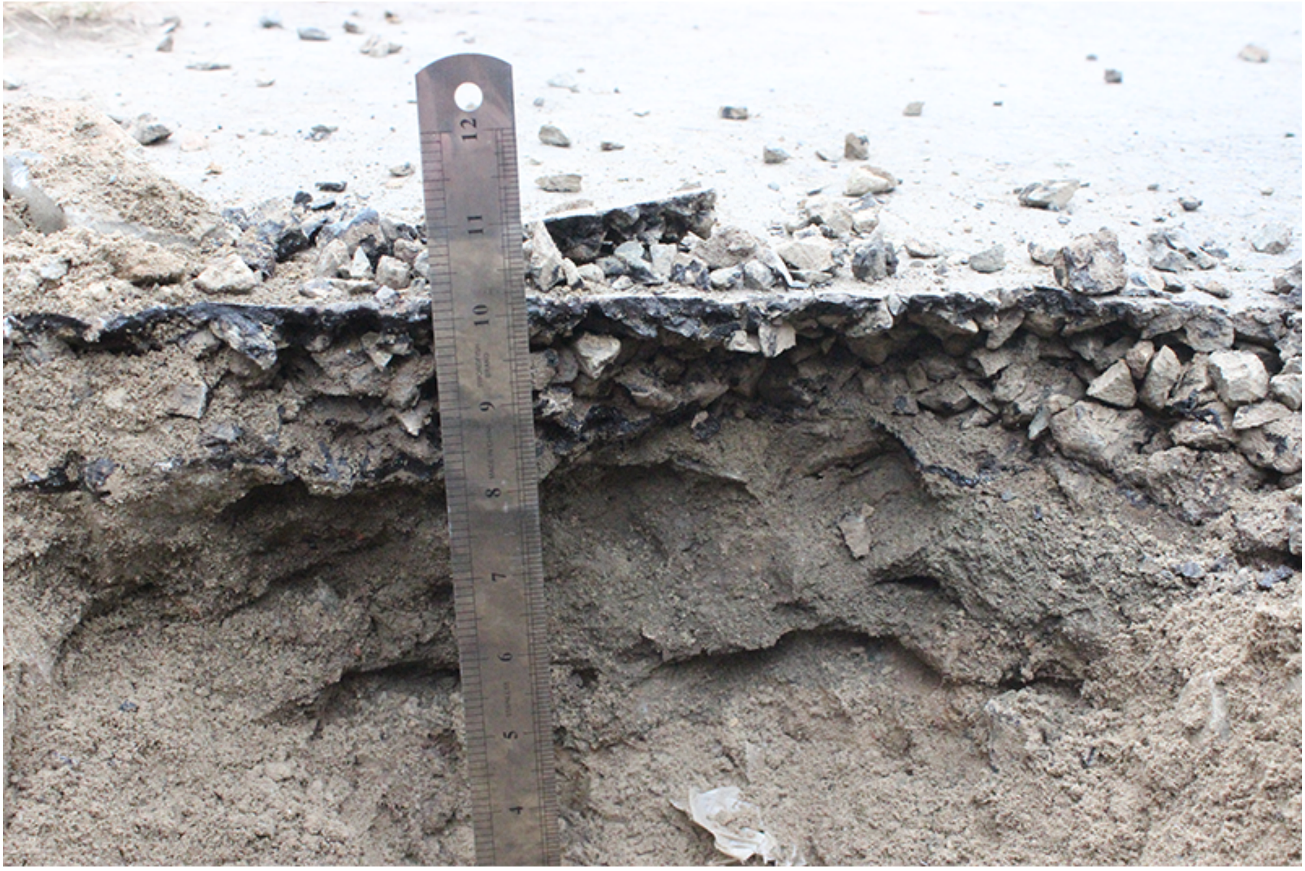
   This test will be performed by taking a handful of stone dust and slightly jerking the hand upwards. Ideally, some of the dust will dissipate in the air while the heavier particles will remain. A video of this process should be made.

Road Layers Test

One standard technique is road testing after construction has been completed is to cut a cylindrical core in the surface and view the layers of compacted material and measure its thickness. This test requires a rather bulky core-cutting machine, which is not easily available in rural areas. However, this test is very critical because a lot of information about the work performed by the contractor can be gleaned from it.

We experimented with generating a low-cost replica of this test that does not require any expensive equipment. This involves digging a hole using a pick-axe (*gaintee*). The hole is dug with care such that soil is removed away from one face, to cause minimum disturbance to the compacted road layers that are left at the edge of the hole. The size of the hole is recommended to be 1ft wide, and it can be upto 8-10 inches deep, depending on the depth of the base level. The edge of the hole is then straightened with a spade (*bailcha*), and then it is photographed by a DSLR camera or smart phone. In our test, we were able to conduct the photography and refill the hole within 15 minutes, on a road that was constructed more than 15 years ago.

The final image acquired by for inspection is shown below, from which our consultant engineer was able to identify several shortcomings in the construction of the road immediately upon reviewing the images.



Consultant Engineer's comments:

Each layer of the road is clearly visible. The thickness of each layer can be determined from the picture. The asphalt layer is much thinner than normal. It should be at least 1.5 inches, whereas here it is about 0.25 inches. The base and sub-base layer appear to have been merged in one layer. Aggregate is of inferior quality with elongated stones present in large quantities.

Our low-cost modification of the core extraction test in road construction is effective, time efficient and can be conducted using readily available digging tools. The test can effectively show information about all stages of construction and can repeated at 500m intervals along the road length. After the test is completed, which takes about 15 minutes, the hole can be filled with concrete, which is an excellent material to bind with the road and will keep it fit for use.

Building Construction

The kinds of buildings we have studied are small schools or health units being constructed. An example of such a building is shown in the picture below. These projects typically take under 6 months to complete depending upon the contractor's pace and size of the building.

The major stages of construction of these types of buildings are given below.

1. Excavation**:** The ground is dug up to the required depth and width. This can be done manually or through an excavator.

2. Laying of PCC or Brick Ballast**:** A layer of Plain Cement Concrete is poured into the excavated ground. Alternatively for smaller projects a layer of brick ballast, which is crushed bricks may be used.

3. Brickwork in Foundation: Bricks are laid over the PCC or brick ballast layer in a pyramid formation with the maximum width of bricks at the base, slowly tapering off to the thickness of the walls to be built in the structure.

4. Damp proof course: This is a layer of polythene, bitumen and concrete that is applied on top of the brickwork at slightly above ground level.

5. Brickwork in structure: Bricks are laid in layers on top of each other to form the walls of the structure.

6. Roofing: Shuttering is constructed on top of which a grid of steel bars is constructed. Bricks are laid in the periphery and concrete is then poured onto the shuttering up to the height of the bricks.

7. Finishes: Walls are plastered with cement and then coated with paint or distemper. Other finishes are also done such as installation of flooring, electric fixtures, doors, plumbing, windows and bathroom fixtures.

In the following table, we discuss each step in more detail, along with sources of corruption at that step and possible imaging protocols to conduct monitoring.

Step 1 : Excavation	Questions to Ask	Sources of Corruption	Possible Imaging Solutions
Excavation to required depth. Foundation is created on which a brick is laid.	Are the dimensions of the excavation as specified?	Contractor may not excavate to required level to save time and subsequent work required to fill and brick work.	Taking picture of excavation with a measure can determine the depth of excavation.
Step 2 : Laying of PCC or Brick Ballast	**Questions to Ask**	**Sources of Corruption**	**Possible Imaging Solutions**
Plain Cement Concrete (PCC) is a 1:2:4 mix of concrete is prepared on site and desired thickness is spread in the excavation and compacted.	Is the ratio of materials in PCC appropriate? Has the concrete been prepared properly? Has the concrete been compacted properly? Is the PCC mix evenly applied to the foundation?	Use concrete with a lower cement to sand ratio to save on cement costs. Contractors prepare the PCC mix all at once for convenience and store it beyond the duration of 40 minutes after which it becomes unsuitable for use. Contractors may not level the PCC mix to save effort.	Taking images of PCC after it has been laid can provide a coarse assessment of compaction, mix and preparation. Determining exact mix is not possible using images.

Step 3: Brickwork in Foundation	Questions to Ask	Sources of Corruption	Possible Imaging Solutions
Brickwork in foundation is laid in layers with the bottom most layer being the widest and subsequent layers tapering.	Are bricks of appropriate quality? Is height and width of brickwork in foundation according to plan?	Contractors use lower quality bricks to save on construction costs Width of foundation is reduced to save cost of bricks	Taking pictures of brickwork from top with a ruler to measure width. Taking picture from the side to measure height.

Step 4: Damp Proof Course (DPC)	Questions to Ask	Sources of Corruption	Possible Imaging Solutions
Damp Proof Course is a layer that is applied on top of the brickwork at foundation. It is composed of three layers, i) sheet of polythene, ii) a coating of bitumen iii) and a layer of concrete (ratio 1:2:4). This step is not very costly but low quality has serious consequences later on in the life of the building.	Is concrete ratio appropriate? Has concrete been compacted properly? Is thickness of concrete layer of Damp Proof Course per specification	Contractors use low cement sand ratio in preparing concrete to save on cost. Contractors may not compact the concrete layer Contractors can use a layer of concrete thinner than specifications.	A picture of the DPC can be used to coarsely determine quality of concrete. It is difficult to determine if concrete composition is appropriate using images. Take a picture of the DPC with a ruler to determine thickness of concrete layer.
Step 5: Brickwork in Structure	**Questions to Ask**	**Sources of Corruption**	**Possible Imaging Solutions**
Layers of bricks are laid on top of each other until the desired height of the wall is reached. Bricks are bound together by mortar, a mixture of sand, cement and water. The brickwork has to be cured for 2-3 weeks.	Are bricks of satisfactory quality? Were bricks soaked before using? Is cement to sand ratio in mortar appropriate? Is width of brickwork according to design? Is brickwork 'in plumb' i.e. has it proceeded vertically? Has the brickwork been cured properly? Have adjacent walls been interlocked properly?	Contractors can use lower quality bricks to save cost. Contractors will use un soaked bricks to save time Contractors will use more sand than cement in mortar Contractors may not interlock walls properly.	It is not possible to tell if bricks have been soaked using images. Taking images of brick walls under construction can provide coarse assessment of quality. It can also provide other information such as if joints are proper and whether adjacent walls have been interlocked properly. Exact test of brick strength requires lab tests. Not possible to tell if cement to sand ratio is appropriate through images. Taking video of plumb line test to determine if work is in plumb.

Step 6: Roof Laying	Questions to Ask	Sources of Corruption	Possible Imaging Solutions
Scaffolding called shuttering is made which will provide a temporary structure on which the roof will be laid.	Is shuttering watertight? Have bricks in periphery been laid?	Contractors may not make shuttering watertight to save time.	Taking picture of shuttering can reveal if there are gaps that would let concrete through.
A grid of steel bars is constructed on top of the shuttering.	Is the diameter of steel as per specification? Is quality of steel as per specifications? Steel should not be rusted, should be made from high quality billet coming from a steel mill instead of from scrap Are steel bars stored properly? Steel bars should not come in contact with the ground. Is spacing of steel grid as per design? Is the clearance of steel grid appropriate?	Contractors will use lesser quantity of steel by increasing grid spacing. Contractors will use low quality rusted steel Contractor may not store steel properly Contractor will use steel with smaller diameter to save on costs.	Taking picture of cross-section of steel bar to determine diameter of bars. Taking pictures of grid to see if spacing is appropriate. Taking pictures of steel bars to coarsely assess quality of steel. Rust on steel bars can be assessed visually in this way but ductility and strength of steel require lab tests. Taking pictures of steel bars on site to determine if they are properly stored.
Once the grids are in place concrete is prepared and poured on the roof. Concrete is prepared by mixing water, cement and aggregate in a mixer on site. It is then transported to the roof, usually in wheelbarrows and poured onto the mesh up to the height of the bricks at the periphery. It is then compacted using a compactor. Concrete also needs to be cured for about 3 weeks after it has been laid to gain strength.	Is concrete mix appropriate? Has concrete been mixed properly? Is concrete workability appropriate? Has concrete been compacted properly? Has concrete been cured properly ?	Contractor may use less cement cost of cement. Contractor may use more water to increase workability of concrete which makes it easier to spread the concrete on the roof and also requires less cement. Contractor may not compact concrete properly. Contractor may not cure concrete.	Since roof is one of the major costs of construction, the entire process should be captured on video to ensure that concrete mix is appropriate. Concrete quality can be coarsely assessed using a slump test that can be easily performed on site. At random points during the process of concrete preparation slump tests will be performed. Pictures of concrete being cured after it has been laid.

Testing Protocols for Buildings

Stage	Testing Protocol	Reason of test	Time of test
At every visit	Zoomed out picture of the site	Orienting the auditor	
	Picture of all material on site	Assess Material quality	
Excavation	Picture of excavation with measure	Geometry of excavated area and quality	At completion
Plain Cement Concrete	Picture of PCC mix on site	Quality of PCC	At start of stage
	Picture of plain cement concrete close to the ground	Level of PCC	At completion
Brickwork in Foundation	Picture of brick walls from each corner	Quality / orienting	At completion
	Picture of all brick stacks on site	Quality of bricks	At start of stage
Damp Proof course	Zoomed-in picture of damp proof course of each wall with measure	DPC quality and thickness	At completion
	Picture of room from each corner or alternatively a 360° picture taken from the center of the room.	Orienting auditor and quality of bricks	At completion
Brick work in structure	Picture of walls from each corner, inside and outside. An alternative to the picture taken from the inside is a 360° picture taken from the center of the room	Brick quality and workmanship / orienting. Determining width of wall	At start, once when wall is 5 feet high and then at completion.
	Close-up picture of each wall	Brick quality and workmanship	At completion
	Picture of plumb bob test	Plumbness or verticality of work	At completion
Laying of grid	Picture of grid taken every 10 feet with a measure	Quantity of steel and grid spacing	At completion
	Close-up picture of steel bar with measure	Diameter of steel bar	At completion
	Picture of steel bars stored at site	Storage	When steel bars brought on site and at every visit thereafter
Concrete pouring	Video of entire pouring process	Quality of concrete by determining inputs such as aggregate and no. of cement bags used	As pouring is taking place
	Video of slump test	Quality and workability of concrete	As pouring is taking place
	Picture of concrete being cured	Curing	Every 5 days after pouring till 3 weeks after
Finishing and plastering	Pictures of all finishes such as: Electrical work / Fixtures Doors Woodwork Windows frames and glass Flooring Plumbing Bathroom fittings	Quality of workmanship, and fixtures.	As each finished item is installed

The above table provided a summary of the protocols. We discuss examples of some tests in some detail below, including comments by our consultant civil engineer about observations that can be made from these images.

At every visit

The monitor will indicate the location of each picture that he takes on the plan uploaded at the time of registration. The smart phone application should present the monitor with the plan of the site, allowing him to mark the location of the picture that he is taking.

1. Zoomed out views for orienting the auditors

2. A picture of all material on site will also be taken.

Foundation

A picture of the foundation with a measure needs to be taken from different points on the site. These pictures were not taken but it will be similar to the picture mentioned in Brickwork in foundation.

PCC in Foundation

1. A picture of the PCC / Brick Ballast mix at the site will be taken.

Consultant Engineer's comments:
The mix is very dry and the aggregate appears to be over sized. The initial setting appears to have been over a long time ago, resulting in a concrete mix of an inferior quality and low strength. The concrete mix appears to be hand-mixed whereas it should have been mixed using a machine.

2. A picture of the PCC mix applied to the foundation will be taken after it has set. Part of the mix will be removed to guage the thickness of the mix. This should be taken with a measure.

Consultant Engineer's comments:

Foundation has been manually excavated. Level of PCC has not been maintained which could subsequently disturb the alignment of the walls. The concrete mix has also not been compacted properly.

Brick work in foundation

1. The picture should be taken so that the height of the brickwork is clearly visible. One picture should be taken from each corner of the brickwork capturing the opposite wall.

Consultant Engineer's Comments: Some bricks appear over-burnt and some have missing edges but overall brick quality is acceptable. Work is also of acceptable quality. Joints are of proper thickness and placed properly i.e. are staggered. Would be good if total width of excavation could be measured through the use of a measure in the photograph.

From Damp Proof Course to Brickwork

1. Photos of the brickwork will be taken from the inside of each room. These photos will be taken from each of the four corners.

Consultant Engineer's Comments:

Quality of bricks and workman ship in this picture is appropriate.

2. Photos will also be taken from the outside of each room for all corners. This will be done until the height of the walls is such that the monitor cannot photograph the top of the wall.

Consultant Engineer's comments
Overall workmanship is satisfactory. Brick quality is also appropriate. Using this photograph width of wall can be determined width of wall which is 13.5" in this case.

2. Zoomed in photos of all walls will also be taken as shown below;

Consultant Engineer’s comments
Bricks and workmanship are of low quality. Joints are untended with missing mortar. Bricks are of low quality, uneven shape and broken corners and over or under burnt. Overall the quality of this construction is very poor.

Polythene for Damp Proof Course is ripped. DPC concrete should be plain and flush with the bricks. Low quality material has been used to make this DPC and will not provide adequate protection against moisture.

3. A plumb line test will be performed as shown in the following picture. The plumb line will be suspended against each wall with the start of the plumb line string clearly visible. This will be done for every wall of the test.

(Image credit: http://estalella20.net/2012/12/la-plomada/?lang=en)

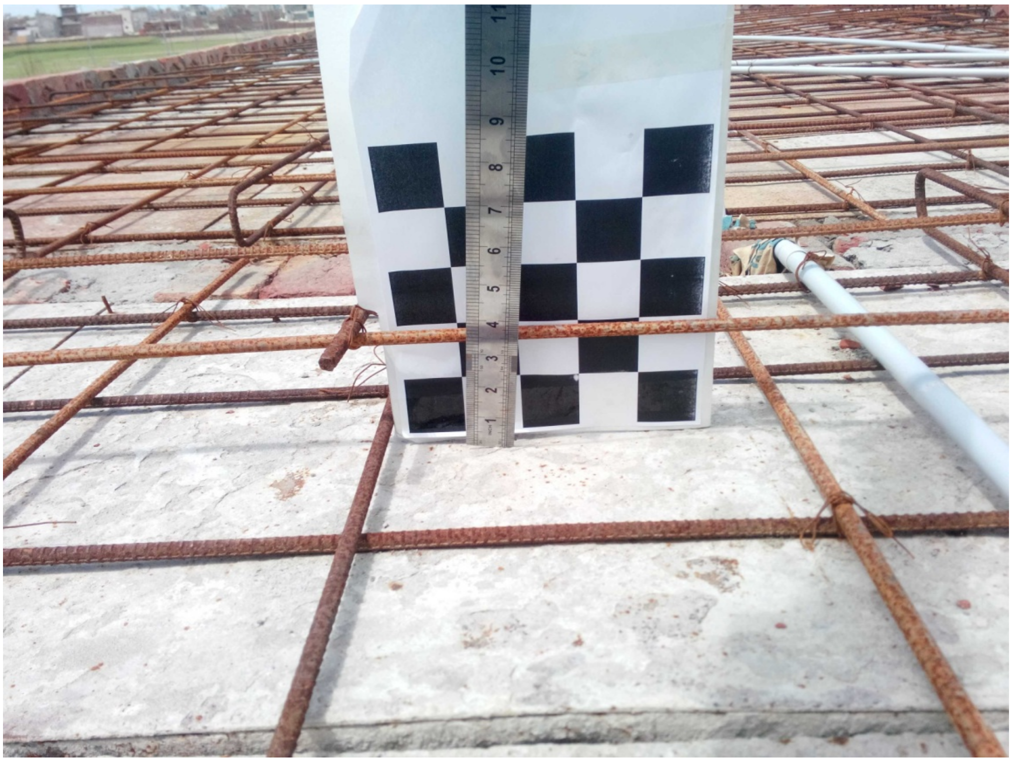
Roof – Laying Grids

1. Pictures will be taken along the narrower side of the roof every 10 feet in either direction.

2. Standard measure should be visible in the picture

Consultant Engineer's comments
Steel bars are rusted and shuttering is not water tight which will lead to bleeding of concrete, cement and water paste. Joints of steel mesh appear to be satisfactory. Grid spacing is consistent and looks to be according to drawing. Spacers for ensuring concrete cover are not present. Bricks are laid in periphery to confine the concrete.

3. A picture like the one below will be taken from 2 spots on the roof such as the one below. Clearance height of bars and binding wires should be clearly visible.



Consultant Engineer's comments :

Steel bars are rusted. No spacers have been placed to ensure appropriate clearance of the bars.

4. Picture of steel bars on site

Roof – Concrete pouring

The monitor must be present all day at the site that pouring is to take place. A video will be made of the entire process. In addition a test known as the slump test will be performed.

1. VIDEO of pouring process

Pouring for small buildings is completed within a day. The entire pouring process will be captured on video, with the mixing machine clearly visible as in the photo below.

Consultant Engineer’s comments:

This is one of the most expensive steps because it uses a large number of cement bags. Through a video of the pouring we can make sure that each batch contains appropriate number of cement bags. During the video a batch of the concrete should be taken aside and a slump test should be performed to assess concrete quality.

2. Slump test

As the monitor is making the video, the smartphone monitoring application will display prompts at the times to initiate the slump test. At these times the mixing and pouring process will continue unabated but a sample of concrete will be taken from the mixing machine and a slump test will be performed on this sample. This test will be captured on video. At no time will the video of the roof pouring be stopped.

Image Credits: www.youtube.com/watch?v=lwZf217v5XA

Consultant Engineers comments
The slump test is an extremely cost effective and simple test that can determine concrete workability and provide a coarse assessment of concrete quality. In these pictures the concrete appears to be of good quality, it has not sheared and the slump appears reasonable. Overall this concrete sample is of good quality.

Limitations of Image-Based Monitoring

The approach we have outlined above has certain limitations but it will be an improvement over current monitoring practices and our hope is that it can act as a strong deterrent against corruption. In terms of cost, the system does not require a lot of trained resources in the field. Anyone who knows how to operate a smartphone can be trained to act as a monitor in the system. The only trained resources required is the team of civil engineers who will be evaluating the data collected from the field. This expense can also be minimized by training less expensive resources without an engineering to audit sites under the supervision of a few trained engineers.

One of the most obvious limitations of the system is that a lot of tests of construction quality require lab testing. However, the quality of construction in the types of projects that we have selected is sometimes so poor that many defects are visually apparent. Moreover, lab testing is seldom deployed for small projects. So at the minimum the system should be effective in preventing the worst instances of corruption. Another potential problem of the system is the risk of collusion of the monitor with the contractor so that the monitor will take pictures such that any quality defects are less obvious. We have defined protocols to minimize the fallout from such a situation. One of the advantages of standardizing protocols is that it leaves less discretion in the hands of the monitor so even if the monitor ends up colluding with the contractor, there will be minimal effect on the process.

Appendix: State of the Art in Image-Based Construction Monitoring

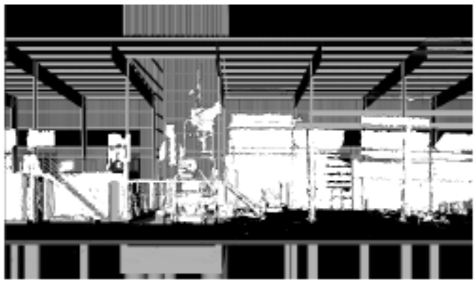
As part of this study we also researched cutting edge research that is being done in the area of contruction monitoring. Some of the most relevant are those that use images of construction since these don't require specialized sensors which can be expensive.

Some prominent groups working on monitoring constructions are :

- RAAMAC (Real-time and automated monitoring and control) at University of Illinois Urbana Champagne. This group recently published a paper that
- Construction Information Technology group at Georgia Tech. This is a group hosted within the department of civil engineering.
- Construction Information Technology group at Cambridge University.

Laser Scanning

Researchers from Carnegie Mellon have proposed the use of laser scanners and embedded sensors to collect data on the built structures and to integrate it with the planned construction model in order to assess any deviations from the original model. They incorporated the as-planned model of construction in the form of information derived from design and scheduling software systems. Laser scanners are then installed in optimal positions to take multiple images of the target site. These scanners generate 3-D point sets called "point clouds" in local coordinate for each scan location [1] (Akinci 13). These different scans need to be aligned into a common coordinate system. The scans can give different kinds of data, such as the positioning or plumbness of columns. In order to compare the as-built data with the as-planned data, this data needs to be further processed in the form of "object recognition" [2] (Akinci 14), whereby local shape descriptors "encapsulate the surface shape of parts of a 3-D object model to be recognized" [2]. Temperature sensors were also utilized in order to determine the strength of cast-in-place concrete in job sites. The cost of on-site laser scanning depends on the type and size of the construction project. The production of drawn output from the collected point cloud data usually comprises 60-70 per cent of the cost of the overall survey, but this may rise to 90 per cent for detailed stonework. If the survey requires photographic colour imaging, different equipment has to be to be mounted to the tripod and so roughly doubles the time spent at each site set-up and adds 10-25 per cent to the overall cost of a survey (Cathedral Communications). This process is economical for basically rectilinear and recent fabric. For instance, the simple facade in figure below was scanned and modeled for £1,350.



Vision based 3-D reconstruction

While the laser scanning method has had success in field experiments, this requires experts to operate it, is expensive and the scanners are not mobile. This system also has a tendency to produce large errors when taking images of thin structures, such as in the case of scanning the positions of rebars. Engineers at University of Illinois-Urbana Champagne have substituted the laser scanners with a 3-D visualization system that is much cheaper and requires only consumer-level cameras or camcorders. In this process, a set of surveying targets is placed on the rebar structure. A field engineer on-site takes multiple images which are then input into an algorithm known as a "panoramic algorithm" (Han) [3]. These algorithms "automatically detect features and match corresponding features from an unordered set of overlapping photos". The system then constructs a 3-D point cloud from the matched points, similar to laser scanners. In this process, the greater the number of digital images that are processed, the higher quality the resulting 3-D image, which has proven to be better than laser images in the presence of occlusion. This system is still in its experimental stages and mainstream manufacturing of the equipment has not yet begun.

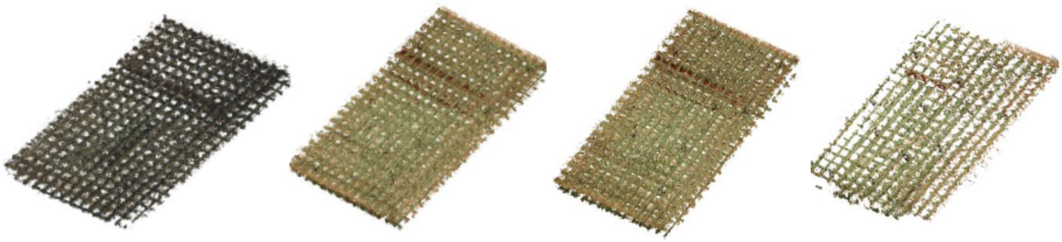


Fig. 4: 3D point cloud models from a) 250, b) 200, c) 150, and d) 100 images

Table 1. Number of points generated from each sample

# of Images	250	200	150	100
Density of the point cloud	13,320,977	10,696,247	11,554,036	1,046,101

Image courtesy of [3]

Lee (2011) [4] used images to detect corrosion in coating of steel bridges. He notes in the paper that:

"Although several rust defect assessment methods were developed in the past few years to evaluate bridge painting surfaces more objectively, they still have limitations when processing digitized images taken under several environmental conditions, which include: non-uniform illuminations, low-contrast digital images, and noises on painting surfaces. These situations are often experienced during bridge painting inspection or image acquisition and dealing with them is not an easy task when developing computerized programs"

Real-Time and embedded sensors

In some cases, sensors have been employed to monitor the density of asphalt used in construction. In one study, a roller-mountable real time asphalt pavement density sensor was installed onto the roller. One antenna was placed at the front and one at the back of the roller. This enabled the researchers to measure differential microwave signals which indicated optimal compaction. Other engineers have utilized sensors that use radio frequency information data (RFID) and GPS to monitor parameters such as "bitumen and asphalt temperatures at various stages of production and spreading, ratios of asphalt components (aggregates, bitumen) in each production batch, average asphalt weight per unit area and theoretical thickness of each layer" [5] (Navon 471). This information is transmitted back to the engineering office where it is analyzed and documented. Construction companies such as Caterpillar and Trimble are now incorporating this technology into their machinery in order to improve and streamline the quality control and monitoring of construction.

Figure 5 Compaction monitoring system

In other cases embedded piezoelectric sensors have been used by Gu et. al (2006) [6] to determine concrete strength at initial setting. Piezoelectric transducers in the form of 'smart aggregates' are embedded into concrete structures as actuators and sensors during casting for strength monitoring purposes.
The authors first calibrated the system from input from sensor embedded in concrete of known strength and then tested the system on new concrete formations. They found that they were able to accurately predict the strength of the concrete using the input form the sensors.

Labour Force Monitoring

Objectively monitoring the labour force has been particularly challenging since live subjects are more difficult to track and data on the productivity of workers usually needs to be manually entered by contractors. However, recently attempts have been made to automate this process. Navon and Goldschmidt used indirect parameters such as the location of a worker as proxies for their productivity. This assumption is based on the idea that in order to construct a building, the worker has to be in physical contact with it and thus, "knowing the worker's location at a given time, together with additional information pertaining to the schedule and the physical design of the building, the activity s/he is working on can be determined" [7] (Navon 473). GPS data regarding the workers' location is used for this purpose and it is integrated with the aforementioned data on construction planning and scheduling.

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