# Failures in Design and Construction and Their Investigation – Case Studies

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**ABSTRACT:** Several significant failures of Civil Engineering Projects ranging from catastrophic to functional failures have been investigated involving structures or structural components.

The causes of these failures have been studied and as a result, remedial measures were implemented. The failures were caused either by design oversights, construction deficiencies and sometimes error in the computerized Analyses and Design Procedures. The cases highlight the need for a greater degree of care and vigilance in the analysis, design, checking and construction of Civil Engineering Projects.

The lessons learned could be put to good use in avoiding the recurrence of similar problems in the future.

For reasons that are obvious, names and some details about the projects have been changed. Any reference to a real person or organization is unintended and purely **coincidental.**

## INTRODUCTION

Failure of Civil Engineering Structures could mean several things. It could be a catastrophic failure or collapse, it could be a loss in functionality or it could mean a degradation in the serviceability of the building to a level that would be uneconomic to maintain.

In the course of the practice of the Profession, Civil Engineers are often exposed to problems in Design and Construction whether done by other professionals or organizations or by the professional himself or his organization. These problems often could result in damage to person or property and involve time consuming litigation. Learning from the past or the mistakes of the past certainly could help the practicing Engineer in avoiding such problems.

It is the intention of this paper to highlight several failures investigated by the author. This paper discusses the failure, the verified causes of the failure, the remediation aspects recommended and the potential cost or damage to parties involved.

For obvious reasons, the names of the persons or organizations involved have been withheld or changed as well as the actual project names.

The intention in presenting these experiences is to aid the profession in recognizing that failures can and do occur in the real world. Experiences of the past are a reliable reference and source of knowledge in avoiding the recurrence of similar accidents.

## 1.0 CASE STUDY NO. 1 - ROOF FRAMING SYSTEM COLLAPSE

### 1.1 Background

A large area warehouse being constructed for XYZ Company had a serious accident. The Roof Trusses fell in Domino Fashion while these were being erected. The accident caused several fatalities, mostly from workmen who were painting the Trusses as these were being erected.

The cause of the accident was immediately attributed to the Erection Crane Boom hitting the front truss resulting in the *"Domino"* like failure. Subsequent investigation, while accepting this as the immediate *"Trigger"* to the failure detected several other deficiencies in construction that led to the catastrophic collapse.

It is noteworthy to mention that deficiencies in the design, although not generally contributing to the failure were

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noted. What is surprising is that these deficiencies were cancelled out by an error in the computer analyses. Thus, a defective design was rendered *"Safe"* by a compensating error. The result was a *"Safe"* design by accident! The general contractor was a reputable company who subcontracted the services of a steel fabricator with very limited experience in structural steel erection. Geometry of the individual trusses also contributed to the collapse as well as substandard procedures employed during the erection.

### 1.2 The Accident

Almost 24 Bays of the Building had received the trusses and purlins were already being installed. Due to the critical schedule, the trusses have been erected only with a primer shop coat. Final painting was being done atop the trusses by several painters as these are erected.

The bottom chords were inadequately braced by light gage **"C"** purlins doubled into a box section by stitch welding.

During the erection, a crane boom hit the front truss causing it to topple, pulling it out of its anchorage and toppling the adjacent trusses one by one in *"Domino"* like fashion.

Several of the workmen painting atop the Trusses fell and were pinned down by the collapsed steel trusses resulting in several deaths.

Immediately on the day after the collapse, we were called in to investigate the cause/s of the accident.

The results of our investigation revealed very surprising details contributing to the collapse.

### 1.3 Investigation

We had to conduct the investigation hurriedly to prevent removal of evidence and in order to interview people involved or have knowledge of the accident. Numerous photographs were taken which served as the incontestable proof of what contributed to the accident. A full peer review of the design was also conducted.

What led to the collapse?
Why did the Trusses topple like dominoes?
Why was the erroneous design not contributory to the failure?
Why did a similar adjacent bent not fail?
These and other questions became clear when we completed the investigation.

### 1.4 Findings

Our findings were as follows:

- **Wrong erection procedures resulted in dangerous connections**

The Subcontractor who fabricated and erected the trusses was not a Structural Steel Fabricator or had very little experience in Structural Steel Fabrication and erection. During the process of erecting the trusses, the trusses became *"short"* because of Elastic Deflection as the trusses were on two or three point pick up. This resulted in the Trusses to be *"bowed"* down thus shortening it.

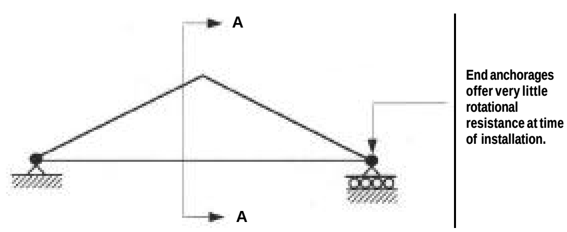
Since the anchor bolts were already cast onto the concrete corbels, the bolt holes on the bearing plates attached to the Truss ends were now out of alignment because of the shortening. In the rush to erect the Trusses, the bolt holes and slots were enlarged to allow the Trusses to be erected.

In most instances, the enlarged holes and slots were wider or larger than the Nuts! Thus, there was no restraint on the Trusses and the anchor bolts were practically useless except a very limited few.

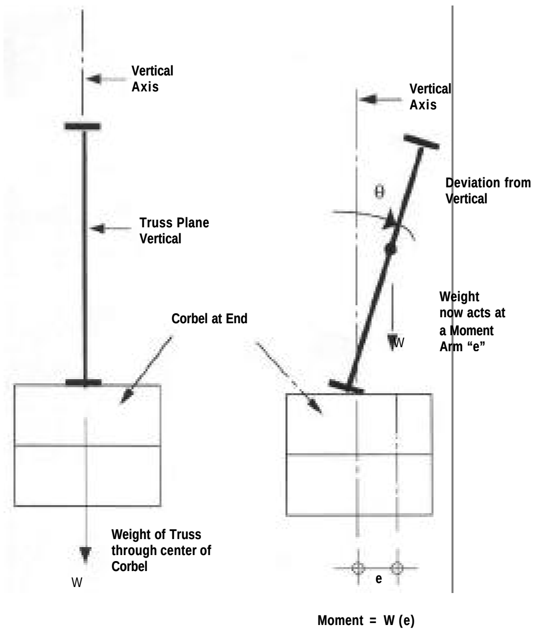
- **Truss Geometry contributed to collapse too**

The Trusses were designed as simply supported Trusses with a Roller-pin connection at the ends. There were two Gables or Truss bents and Bent 'A' was being erected while Bent 'B' was already erected.
Inspection of the finished Bent 'B' showed the same deficiencies and defects.

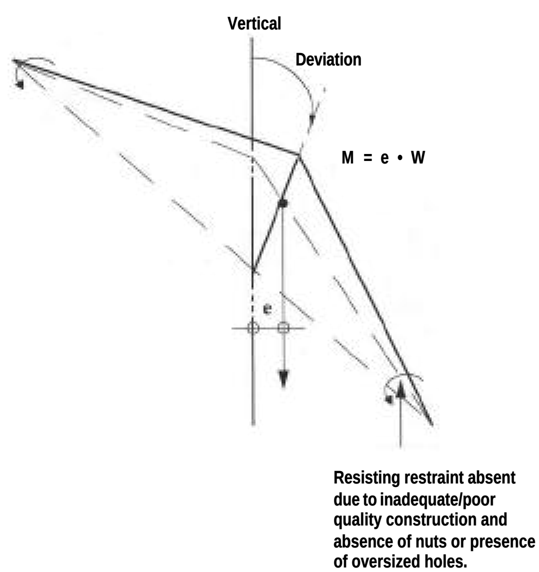
The figure below shows the unfavorable geometry represented by a triangular shaped truss. Vertically, the system would be *"Stable"*. However, once there is lateral disturbance, the system failed by toppling progressively.




**1. MODEL OF TRUSS SYSTEM**




**2. SECTION AA**




**3. ROTATIONAL MOMENT "M" CAUSED BY TILT OF TRUSS FROM VERTICAL**

As can be seen, this unfavorable geometry offered very little rotational resistance when the Trusses were loaded laterally. In some of the Truss ends that did not fall, the Truss ends were restrained by the bolts but toppled on its side just the same because the ends were twisted due to lack of rotational resistance.

- **Substandard Horizontal "Struts"**

The horizontal bracing or *"Struts"* for the top and bottom chords of the Trusses used substandard and poor quality construction.

The struts were assembled from two Light Gage **"C"** purlins which were joined by widely spaced stitch welds. The *"Struts"* simply buckled progressively as the Trusses Toppled.

- **Design made "Safe" Accidentally**

There were numerous and sometimes serious design deficiencies noted during the Peer Review process. However, and as earlier stated, the design process did not contribute to the collapse because a subsequent error in the computer program caused by a *"Bug"* in the software tended to compensate for the **underdesigned** columns by over designing these!

Thus, the design was rendered safe by a computer bug.

Our finding in the peer review revealed that:

- The Building would have been grossly *underdesigned*. The gross deficiency could have resulted in a collapse under design loading conditions had it not been for a compensating error due to the software *"Bug"*.

The following are the deficiencies:

- **Column Design**

Incorrect wind and earthquake loads were used. Wind forces applied to the roof were all positive *(Downward)* when in fact the governing loads were negative *(suction pressures)* for the roof pitch used.

The columns were designed using a popular Integrated Structural Analysis and Design Software. The *"Bug"* tended to overdesign compression members.

Seismic Loading and Building type classification were entirely wrong . Gross underestimate of the base shear resulted in a 60% reducting in Seismic Loading. The building was classified as an OMRSF – Ordinary Moment Resisting Space Frame which for a concrete structure is prohibited by the code in Zone 4.

- **Truss Design**

The analyses considered that the Truss members were rigidly connected yet the Trusses were designed as axially loaded members only, totally neglecting the moments.

The saving grace was that for the Bottom Chord and also the Top Chord, only the maximum stress was used in the design. Similarly for the web members, only very limited stress values were used. While the analyses veered towards underdesign, the resulting over simplification in the design tended towards overdesign except for a few members.

This cancelled out the problem but resulted in a very heavy and expensive roof truss. The resulting overdesign due to simplifications and accidental errors resulted an increase in the Truss weight by 30%!

- **Height of Structure**

The height of the structure as used in the analyses and design was 10.0 meters. The actual height was 15.0 meters.

It can not be ascertained when and at what point was the height changed. This should have automatically triggered a redesign.

- **Concrete columns considered as purely axially loaded members**

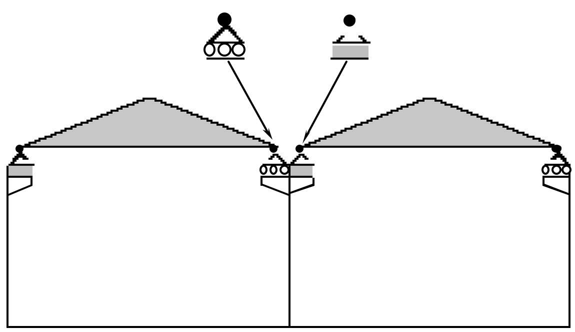
The computerized Analysis Loading Diagram clearly showed that the Truss reactions were co-axial with the column centerline.

In actual fact, the trusses were supported on 500mm corbels and hence induced bending moment on the columns.

This could have resulted in an underdesign of the columns if not for the *"Bug"* in the computer program.

- **Overall Roof Framing System is Inefficient**

The Roof Framing System adopted consisted of two Truss Bents resting on corbels in a Roller/Pin connection detail as shown below:



Thus, the Truss Bents could not participate efficiently in carrying lateral loads and redistributing loads as these are essentially simply supported elevations. Thus, there are no redundancies in the structure nor alternative stress paths in case of overstress.

### 1.5 Lessons Learned

1) Erection is a critical operation requiring care and experience. It can not be entrusted to inexperienced contractors.
2) The use of torches to enlarge the anchor bolt holes should not be allowed at site without adequate technical supervision.
3) Use of substandard struts and purlin connections allowed the collapse to propagate to adjacent trusses.
4) Unstable truss geometry allowed the collapse to become a total system failure.
5) Although the design was not the cause of the collapse, gross oversights and deficiencies occurred such as:
   - Errors in loading assumptions
   - Computer code errors were unchecked
   - Wrong computer modeling
   - Lack of peer review checking procedures

## 2.0 <u>CASE STUDY NO. 2 - ALTERNATIVE DESIGN RESULTED IN DEFECTIVE STRUCTURE</u>

### 2.1 Introduction

Our firm was engaged to design a large Industrial Complex for ABC Company. Part of the Complex was a large area warehouse with a floor area of approximately 4.0 Hectares (40,000 sq.m.).

When the project was bid, the low bidder offered an alternative design build proposal which was P20M lower than their offer using our design.

Because of the potentially huge savings, the owner opted for the alternative design build proposal.

This proved to be a mistake!

### 2.2 Problem Detected

Six months into the construction and when 4 hectares of purlins have already been laid and all structural framing are waiting only for the roofing and cladding installation, the owner's Project Engineers noticed deflections in the purlins and trusses based on pure deadweight alone. The owner had to engage our services again to conduct a peer review of the Contractor's design.

Subsequently, a professional waiver was obtained from the Contractor's Engineers for us to undertake a professional design review.

### 2.3 Findings

A study of the design calculations and loading data revealed very startling facts.

1. Wind pressures used were very much below Code values and neglected exposure factors due to location which would have further increased the wind pressures and in some locations uplift pressures would have been doubled.

*Note:*

*The warehouse is situated along a flattened slope fronting the sea. Exposure factors for this should have been $C_e=1.51$ for Exposure Category D.*

In some critical areas, wind load was inadvertently not considered.

2. The computational model used by the Contractor's Engineer resulted in a *collapse mechanism* as all the joints for the columns were *"pin"* connections as well as the truss to column connections. This is statically inadmissible.

   Lateral loading in the computer analyses would have already triggered or signaled a **"Fail"** condition but this was missed or was neglected.

   Fortunately, in actual construction, the column anchorage connections indicate that it is *"semi-fixed"* condition as the anchor bolt details are not indicative of a pinned connection.

3. Loading assumptions used in design were 50% lower than code provisions.
   This would have directly resulted in a structure that would also be underdesigned by this magnitude.
   However, other errors contributed to a gross underdesign.
   Seismic loading *(although not significant)* was entirely neglected.

### 2.4 As Constructed Members Deficient

As a result of the foregoing erroneous assumptions and incorrect modeling of the structure geometry and fixity conditions, the following were our findings:

- Truss members were grossly inadequate for the actual design loads.
- Columns now with partial fixity assumed in the peer review were *"safe"*.
- Purlins exceeded allowable stress limits by as much as 100% and violated deflection limitations.
- Wall furrings exceeded allowable stress limits by 100%.
- Truss carrier girders were designed based on unrealistic slenderness ratios resulting in underdesigned members.

### 2.5 Software Bug Contributed to Error

In the course of our review, we noted further that the allowable stresses for compression members used by the Contractor's Engineer were relatively high compared to our computer results.

We were using the same program but the Contractor's Engineer used a newer version (Ver. 22) and we used an older but licensed version.

We then proceeded to calculate the allowable stresses in compression by hand and we were able to verify that our calculations were correct.

Still, the Contractor's Engineer was insistent that their calculations were correct considering that they were using a newer version! In order to resolve the matter, we wrote an official letter of inquiry to the Software company. They immediately replied by admitting to a bug when they revised the new version! This finally laid matters to rest. We provided a copy of our findings to the Owner and Contractor's Engineer.

### 2.6 "Value Engineering" Turns to Financial Disaster

As a result, 4.0 hectares of already erected purlins were totally removed and replaced. We prepared remediation measures for the trusses by providing cover plates for all overstressed members and beefed up the longitudinal bracing and carrier girders. The exercise proved to be a costly one, both for the contractor and the owner.

- The owner suffered 2.5 months of delay in the project. They were also forced to hire outside storage space for sensitive electronic equipment and controls for the industrial plant.
- The contractor suffered a huge financial loss. Defective purlins covering an area of 4.0 hectares were totally removed and replaced. Expensive reinforcement coverplating operations involving overhead welding work were performed on the trusses while these were on temporary supports.
- We are not aware if the owner slapped penalties on the contractor.

### 2.7 Lessons Learned

1. Computer programs can not be given blind trust.
2. Entrusting design to inexperienced Junior Engineers could result in disaster.
3. Oversights in the interpretation of code prescribed loadings and exposure factors was a major contributor to the problem.
4. Proper in-house review could have already detected a statically inadmissible collapse mechanism but this was not detected at all until it was too late.

## 3.0 <u>CASE STUDY NO. 3 - NEAR PANIC CAUSED BY WRONG DETAILING</u>

### 3.1 Introduction

This failure was not as significant financially or technically as the Near Panic it raised. The remediation nevertheless proved to be costly.

The project is an ultra hygienic sanitary facility for the manufacture of infant formulation. The facility is for spray drying liquid milk to powder form.

Entry is strictly limited requiring gowns, head covers, removal of wrist watches and eye glasses, use of disposable shoe socks and alcohol hand washing.

The facilities manager was in near panic when black stains were found between the column/masonry joints. It was immediately suspected as *Bird Droppings* as the blackish color would indicate. Bird droppings is the most common source of the dreaded *"Salmonella"* bacteria. Any reported occurrence could have required a total prolonged shutdown and sterilization of the Seven Storey Spray Drier Tower.

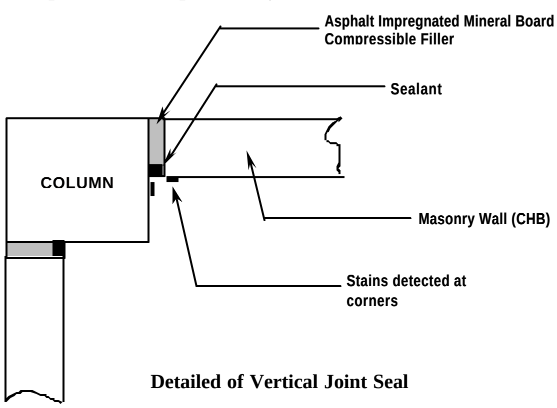
We were called in to provide consultation. We inspected the location and true enough, we verified the presence of black stains along the vertical joints between the columns and masonry wall. This was very alarming indeed having been briefed about what would be the repercussion when *"Salmonella"* is detected in an otherwise ultra hygienic facility.

### 3.2 Instant Problem Identification

We immediately proceeded to the Engineering office of the manufacturer to look at the As-Built Plans.

What we saw immediately identified the problem.

The problem is explained by the sketch:




**Detailed of Vertical Joint Seal**

A clear study of the detail above clearly showed that the joint seal placement was r**eversed!**

The Asphalt Impregnated Mineral Board Compressible Filler was exposed to the elements and the sealant was placed inside. Weathering and exposure to sunlight melted the asphalt and degraded the mineral fiber.

Breaks in the sealant allowed the melted asphalt diluted by water to find its way inside and was initially suspected as stains from bird droppings which equates to potential salmonella infection.

### 3.3 Remedial Measures

The remedial measures recommended and instituted was simple but very costly.

It required removal of these numerous vertical joints throughout the Seven Storey Facility and replacement with proper jointing procedures. This was very expensive for the owner.

### 3.4 Lessons Learned

Even very simple and seemingly innocent mistakes in small details could cause problems if not checked by a built in checking and review process.

## 4.0 <u>CASE STUDY NO. 4 - SINKING OR RISING?</u>

### 4.1 Introduction

A very large specialty packaging materials printing plant was constructed partly on cut and partly on fill. Two thirds of the plant was resting on compacted fill material.

A very expensive four color offset printing equipment costing tens of millions of pesos was installed. The offset machine consisted of four presses connected by a drive rod about 35mmØ. The machine sits on a thick mat foundation integrated with the floor slab. The offset machines required very small tolerances and any misalignment horizontally or vertically would be intolerable as it would result in inexact color laying and printing.

Soon after commissioning, the printing machinery was wasting a lot of expensive rolls of materials due to misalignment. Corrections were periodically being made but the problem became worser with the passage of time until production was totally stopped for this machine. The whole production schedule was in jeopardy.

The Building footprint was surrounded on two sides with depressed areas that ponded water during heavy rains due to inadequate drains.

### 4.2 The Problem

The owners as well as the foreign equipment supplier immediately suspected settlement as the probable cause.

We were invited to visit the site in order to look at the problem.

What we saw was contrary to the owner's suspicions as the machinery was actually **rising** and not settling!

When we informed the owner about our initial findings he could not believe what he heard. Nevertheless, he engaged our services to prove it and recommend remedial measures.

### 4.3 The Investigation Program

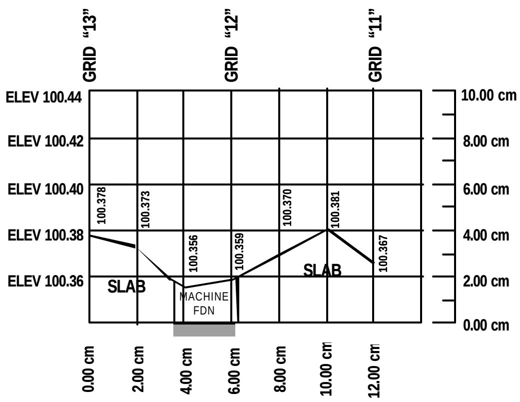
We recommended a fourpart investigation program *(subsequently accepted)* consisting of:

1. Undertaking Elevation Survey *(Topographic)* of the immediately affected area.
2. Undertaking five shallow test pits to extract soil samples.
3. Performance of laboratory testing to determine swelling characteristics and swell pressure of extracted soil samples.
4. Study of surrounding terrain and drainage areas.

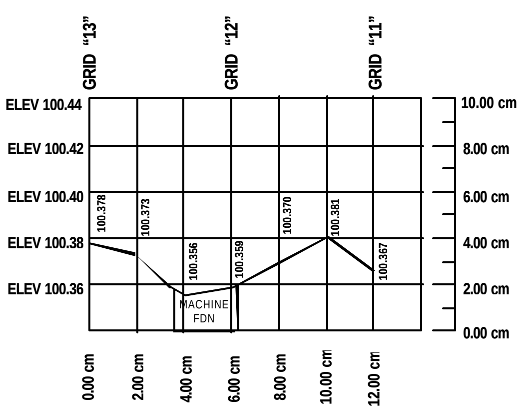
The results of the investigation program were formalized in a report including our remediation procedures.

### 4.4 Results of the Investigation

The investigation results corroborated our initial findings. The Topo Survey confirmed that the slabs were indeed rising and dragging the equipment up.




11 TRANSVERSE CROSS-SECTION (GRID R)
C-1 C-1 SCALE HOR. 1 : 200 MTS



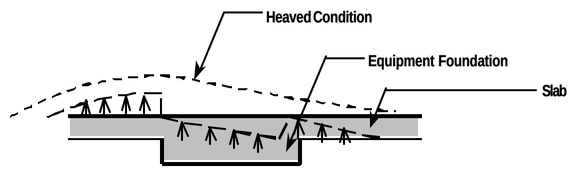

11 TRANSVERSE CROSS-SECTION (GRID R)
C-1 C-1 SCALE HOR. 1 : 200 MTS

A section through the longitudinal and transverse axes of the equipment revealed the vertical heaving of the slabs as well as the equipment foundation without a doubt.

The laboratory tests also essentially proved the swelling tendencies of the soils. Most of the Fill material underneath the slabs classified as CH/MH with LL>55 PI>25. The swell potential is from medium to high with swell indices as high as 10 in most cases.

Generated swell pressure in confined swell tests indicated a swell pressure of **744 psf *(35.6 kPa).*** Based on calculations, this swell pressure alone would not have been sufficient to lift the heavy mat foundation. Therefore the question: why did it rise? became a priority to be answered.

Inspection of the floor slab and equipment foundation gave the answer. The floor slab was connected to the equipment foundation and were cast monolithic with rebars being continuous.
This provided a connection to the slab. When a large area of the slab was heaved, the large force accumulated was sufficient to pull the machine foundation upward. The problem is illustrated below:




### 4.5 Mechanism of Failure due to Heaving

### 4.6 Remediation

#### *4.6.1 Background*

The slab distress definitely has been caused by Swelling/Heaving and it is only necessary to establish by what mechanism this has occurred in order to come out with proposals to solve the problem.

It must be understood that any solution of total removal of the swelling soils would not entirely eliminate the swell potential.

In addition, the presence of entrapped water in the form of Natural Moisture Content of the existing soils, which is relatively high based on laboratory test on test pit samples, could trigger further settlements. This is still possible even if remedial intervention.

#### *4.6.2 Water Saturation by Ponding*

The drainage of surrounding low lying areas around the plant is impeded or prevented by the absence of adequate drainage structures and outlets. Thus, surface runoff accumulates and the surrounding areas become a detention pond which saturates the area.

Water has a natural tendency to migrate from hot to cold areas. Since the plant footprint is shaded by the roof, insulated by the floor slab and is well ventilated, the underlying soils are definitely cooler inside than outside the plant footprint.

Thus, a thermal gradient is set up and water follows this gradient. The attractive forces are greater than gravity forces, and therefore water can rise up also aided by capillary action as to cause Swelling of the Highly Plastic Soils ***(CH/MH).***

### *4.6.3 Mechanics of Swelling Soils*

Since expansive soils are characterized by very fine granulometry and thus large surface area to mass ratio, it has a great affinity for water. Water is captured and absorbed by the water and held tightly with great attractive force.

The absorbed and adsorbed water increases with further attraction and volumetric expansion as swell occurs. Since the affinity due to powerful electrical and chemical forces of attraction is great, the expansion generates tremendous pressure when confined or restrained. This results in high swell pressures that could lift lightly loaded slabs or machine foundations.

Therefore, the key to further swelling is the presence of water. Since the swelling process is reversible in a sense, alternate wetting and drying as would occur during periods of rain and drought would cause shrink and swell, shrinkage causes collapse of the soil structure and therefore aggravates and accelerates pavement deterioration.

Based on this, it is also necessary to attain equilibrium of moisture condition to prevent seasonal and cyclical volumetric changes.

Thus, the primary direction for the solution of problems related to swelling soils, if the swelling soil can not be removed and replaced is:

- Elimination of sources of water
- Maintenance of moisture equilibrium within the critical area which in this case is the plant footprint.

## 4.7 Proposed Remedial Measures

We have divided our recommendations on the mitigation and prevention of further swell damage to **most urgent** and **immediate.**

### *4.7.1 Most Urgent*

We have recommended the cutting or uncoupling of the accidental connection or friction joint between the slab and the machine bases.

We also recommended that the general floor slab be uncoupled or connections cut along the perimeter and interior walls. This would be necessary to release the restraint which could cause further cracking of the slab.

The cut was done by a diamond cutting wheel. The cut was then sealed by elastomeric sealant that is solvent and oil resistant.

### *4.7.2 Immediate Solutions*

*Elimination of Sources of Water*

1) Swales and ponded areas were regraded to divert water from the plant footprint. Backfill was compacted after the subgrade has been cleaned and grubbed and also compacted to 95% MDD based on ASTM D-698.
2) Effective drainage away from the site was implemented to remove ponding and detention of water.
3) Roof drains and collectors *(RCP Pipes)* near the plant perimeter were decommissioned and replaced by lined ditches at least 2.0 meters away from the plant footprint. This will ensure that any leaks or breaks are clearly visible. The downspouts now drain directly into these trenches.
4) Footpaths along the Building perimeter have reversed slopes due to Swelling allowing water to seep into the building. These were reconstructed by additional concrete topping sloping away from the building as shown in Fig. 1.0.

### *4.7.3 Recommendation for Preventing Further Water Ingress and for Maintaining Moisture Equilibrium*

To prevent additional water ingress underneath the Building footprint, it was necessary to provide an **impermeable** Barrier Wall. The Barrier Wall was constructed as near as possible to the Building perimeter and extended at least 1.5 meter vertically below Finished Floor Line.

This Barrier consisted of an HDPE Liner 2mm thick and with all joints fusion welded to ensure that there are no breaks in the impermeable barrier. The trench was backfilled by Compacted Fill and the top impermeabilized by concrete pavement.

The Schematic Sketch is shown below:

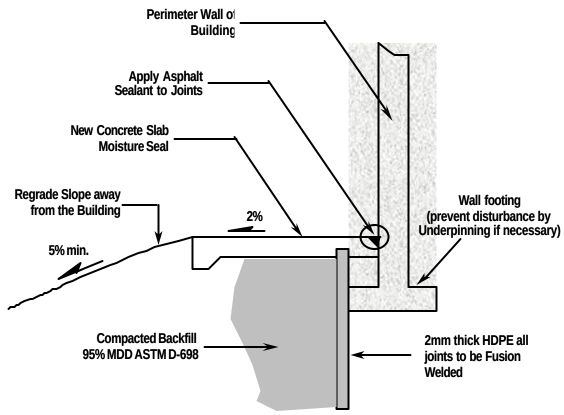



**Fig. 1.0**

### 4.8 Lessons Learned

1) Care should be exercised in the selection and classification of Fill soils underneath structures.
2) Water ponding around structures should be avoided as these will eventually channel water underneath the structure.

## 5.0 CLOSURE

There are still other failures that needed to be presented. However, the other cases were caused by the now all too familiar reasons:

- Professional Negligence
- Computer Error
- Inexperience
- Construction Oversights and Negligence
- Lack of Quality Control, etc.

As Civil Engineers, we have the duty to our clients and the public in general to provide safe and functional structures free from defects and complying with regulations. A study of the past certainly is one way of avoiding similar mistakes.