RESEARCH REPORT

LONG TERM PERFORMANCE OF SLAB-ON-GRADE HOUSE FOUNDATIONS IN REGINA, SASKATCHEWAN

EXTERNAL RESEARCH PROGRAM

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Final Report

Long Term Performance of Slab-On-Grade House Foundations in Regina, Saskatchewan

Submitted By

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October 20, 2004

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Abstract

This study is an investigation of the long-term performance of slab-on-grade foundations for low-cost houses built in Regina Saskatchewan from 1955 to 1960. These shallow foundations and other innovations made it possible to construct 90 m^2 (969 $feet^2$) houses on 15 m by 37 m (50 foot by 100 foot) lots which sold for under $10,000. Unfortunately, for many of these houses, the swelling and shrinking behavior of the deep Regina clay subsoil soon began to affect their shallow foundations. Occupants noticed during the first few years of occupancy that the central areas of the floor appeared to be settling and partition walls appeared to hang from the roof trusses. This "dishing" of slabs was more pronounced in winter and somewhat relieved in summer. A number of houses were mud jacked to restore to level. This procedure was not a permanent fix and movements of treated and untreated slabs continued both seasonally and over the longer term.

In 1960 the Prairie Regional Station, Division of Building Research, National Research Council of Canada was invited to monitor the behavior of these and other innovative foundations built at that time. Monitoring continued until the late 1970's when the houses were approximately 20 years old. This investigation in 2003 re-examines these houses after approximately 45 years of service.

The combined effects of covering the ground with an impermeable slab, shading by the building, irrigating, planting trees and shrubs, snow clearing and disposing of roof drainage created new dynamics for subsoil moisture which in turn caused new swelling or shrinking reactions by the clay rich subsoil. Where no trees were planted close to slabs, the slabs progressively heaved at different rates depending upon exposure and moisture availability. This heaving might typically exceed 100 mm (4 inches). Where deep-rooted vegetation grew too close, the affected floor slab might have settled 100 mm (4 inches) or more. Where slabs-on-grade are impacted by both swelling and shrinking subsoil the differential movements can exceed 200 mm (8 inches). In spite of such large distortions all of the original slab-on-grade houses are still in service.

Without major changes in design and construction to cope with or eliminate these large and on-going ground movements it is not recommended that slab-on-grade foundations be chosen in future for houses in Regina or other locations having similar geology and climate.

Executive Summary

The objective of this project was to undertake a field investigation of the long-term performance of slab-on-grade house foundations built between 1955 and 1960 in Regina, Saskatchewan. In 1960 the Prairie Regional Station, Division of Building Research (DBR), National Research Council of Canada (NRC) was invited to investigate the causes and magnitude of movements which had become concerns to owners/occupants, building officials and the house building industry.

More than one hundred of these homes were located and inspected in 1960, and a few were selected for performance monitoring through the 1970's. During the same period of time a number of conventional and innovative basement and crawl space foundations for houses were also monitored by DBR, NRC.

The 2003 investigation included contacting the current owners/occupants, seeking permission to visit and complete a questionnaire and visual assessment and, where desirable, conduct floor surveys and soil testing. Seventy-six of the current owner/occupants participated in the questionnaire. Thirty-six slabs-on-grade were level surveyed. Five locations were selected for soil moisture investigations.

All of the slabs-on-grade examined in this study have suffered excessive differential movements by all code or engineering standards. The 36 floor surveys found differential movements ranging from 40 mm (1.6 inches) to more than 200 mm (8 inches) with a median of approximately 100 mm (4 inches). Attempts by specialist contractors to re-level some of these houses by "mud-jacking" (selectively injecting cement grout into subsoil to raise and re-level above lying slabs) have met with varied success. Several of these homes have been treated more than once since the late 1950's. Owners have reported improvements in floor levels for several years followed by return of movements after 7 to 10 years.

Perhaps surprisingly, occupants of the houses were generally tolerant of conditions that might not be accepted elsewhere in Canada where swelling and shrinking subsoil are unknown. All of more than 100 houses identified in 1960 are still in service. Occupants generally expressed levels of satisfaction for these low initial cost homes even when taking into account relatively high repair and maintenance costs. Maintenance levels varied but generally were consistent with neighboring homes. Street appearance was generally good and the majority had undergone normal exterior renewal and redecorating. From the street the untrained eye would probably not detect the amount of distortion these houses have experienced. Frequent interior repairs and redecorating has covered much interior plaster cracking over the years. The sloping floor surfaces are tolerated by occupants of varying ages including several confined to wheelchairs. The remaining original owner/occupants are quite elderly and find easy interior and exterior access without stairs a main reason for remaining in these homes.

Résumé

L’objectif consistait à étudier sur place la performance à longue échéance des dalles sur terre-plein de maisons construites entre 1955 et 1960 à Regina, en Saskatchewan. En 1960, la station régionale des Prairies de la Division des recherches sur le bâtiment (DRB) du Conseil national de recherches du Canada (CNRC) était invitée à étudier les causes et l’ampleur des mouvements qui préoccupaient les propriétaires ou occupants des maisons, les agents du bâtiment et le secteur de la construction résidentielle.

Plus d’une centaine de maisons du genre ont été repérées, puis inspectées en 1960 et quelques-unes ont été retenues pour fins de contrôle de la performance au cours des années 1970. Pendant la même période, des sous-sols et vides sanitaires classiques et innovateurs ont fait l’objet d’un contrôle de la part de la Division des recherches sur le bâtiment du CNRC.

L’enquête de 2003 consistait à demander aux propriétaires ou occupants établis la permission de visiter les lieux et de remplir un questionnaire et de faire une évaluation visuelle, en plus, là où c’était souhaitable, de procéder à une vérification de la dalle de plancher et à une analyse du sol. Soixante-six des propriétaires ou occupants ont consenti à remplir le questionnaire. Le niveau de trente-six dalles sur terre-plein a été vérifié. Cinq endroits ont été retenus pour fins d’analyse de l’humidité du sol.

Toutes les dalles sur terre-plein étudiées au cours de la recherche avaient subi un mouvement différentiel excessif par rapport aux exigences des codes ou des normes d’ingénierie. Les 36 dalles de plancher accusaient un écart variant entre 40 mm (1,6 mm) et plus de 200 mm (8 po), la moyenne se situant à environ 100 mm (4 po). Certains entrepreneurs spécialistes du domaine ont tenté de remettre à niveau certaines maisons (en injectant de manière sélective du coulis de ciment dans la couche du sous-sol pour surélever et remettre la maison à niveau au-dessus des dalles en place) ont connu un succès relatif. Plusieurs de ces maisons ont fait l’objet de travaux correctifs plus d’une fois depuis la fin des années 1950. Les propriétaires ont signalé une amélioration pendant plusieurs années, mais constaté que le problème se manifestait de nouveau après 7 à 10 ans.

Fait peut-être surprenant, les occupants des maisons toléraient généralement une situation qui ne l’aurait pas été ailleurs au Canada où les effets du gonflement et du retrait du sol sont inconnus. Toutes les maisons parmi plus de cent qui ont désignées dans les années 1960 sont toujours en service. Les occupants ont généralement exprimé leur degré de satisfaction à l’égard de ces maisons assorties d’un coût original faible, même en tenant compte des coûts élevés de réparation et d’entretien. Les niveaux d’entretien variaient, mais correspondaient en règle générale à ceux des maisons avoisinantes. De la rue, elles présentaient généralement un bel aspect et la majorité avaient subi des travaux normaux de remplacement et de redécoration. De la rue, un profane ne discernerait peut-être pas les déformations que ces maisons ont subies. De fréquents travaux de réparation et de redécoration intérieurs ont réussi au fil des

ans à camoufler les fissures du plâtre. Les occupants de différents âges tolèrent l'inclinaison des planchers, dont plusieurs confinés à un fauteuil roulant. Les autres propriétaires ou occupants d'origine, plutôt âgés, trouvent l'accès facile autant à l'intérieur qu'à l'extérieur, vu l'absence de dénivellation; voilà d'ailleurs une des principales raisons expliquant leur volonté d'y demeurer.

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1 Introduction

The house building industry in Regina, Saskatchewan has a long history of seeking economical foundations for low-cost residential construction. The geology and climate combine to make this particularly challenging. A very deep deposit of highly expansive clay underlies most, if not all, of the city. A semi arid climate coupled with the desire of homeowners and city officials to create a lush green environment complete with shrubs and trees makes landscape irrigation a necessity and adds to the complexity of foundation problems. Roofs and pavements distort the natural infiltration of rainfall and snowmelt. Landscaping and underground services add further complexity to the active zone around and below shallow foundations. In the open field, the ground surface heaves as the active zone increases in water content and settles as it dries due to evaporation from the surface and through plant transpiration processes. Trees and lawns each need approximately 500 mm (20 inches) of water infiltrating the ground surface during the growing season but the normal rainfall during this period is only 280 mm (11 inches). The difference must be made up by irrigation or the result will be soil moisture depletion and vegetation stress. In the longer term, deep-rooted shrubs and trees extract water from a deepened active zone especially during extended periods of drought and competition for sparsely available soil moisture.

Clay soils shrink as soil moisture is depleted and swell when moisture is replenished. Frost heaving in the winter is seldom of significance unless the freezing clay is exceptionally wet. Clay at low moisture contents often shrinks during freezing. Thermally activated movement of soil moisture appears to be of significance around heated and/or cooled structures. Excavation of overburden to permit installation of footings, basement walls and floors results in an unloading of subsoil below the basement floor level which results in increased heaving when the subsoil gains access to water. Although full and partial depth basements have been the predominant choice for single-family houses in Regina during the past 50 years, their performance and economics of operation are dependent on on-going intelligent adjustments and maintenance. Without vigilant care (often beyond the capabilities of occupants) their long-term performance may not be significantly better than those of basementless alternatives. Slabs-on-grade and crawl-space foundations offer economics of initial and operating costs where basements are not essential. Incremental upgrading of the 1950’s and 1960’s designs and construction of slab-on-grade and crawl space foundations may provide better long-term performance for these alternatives. To produce equally improved performance for similarly sized basements may be more expensive. The condition of a sampling of 40-50 year old slab-on-grade foundations for houses in Regina, Saskatchewan was examined and evaluated in this research study sponsored by Canada Mortgage and Housing Corporation (CMHC).

2 Scope and Objectives

During the 1950's and 1960's many low cost, single-family dwellings were constructed in Regina on conventional basements, slab-on-grade and crawl space foundations. Samplings of these were documented and performance observations commenced by the Division of Building Research (DBR), National Research Council of Canada (NRC). A representative sampling of each foundation type was instrumented and monitored at increasing time intervals through the 1970's. Many of these innovative foundations have now reached 40-50 year service lives and original or long-term owners occupy some. The financial contribution from CMHC's External Research Program and the cooperative efforts of J. J. Hamilton P. Eng. and Clifton Associates Ltd. facilitated a unique opportunity to document this long-term performance while the original researchers and their records and some of the original homeowners are available.

It was proposed:

1. That the study include the houses identified in the 1960's studies of the Prairie Regional Station of the Division of Building Research, NRC;
2. That these houses be revisited and the performance of the foundations be observed and recorded for comparison with previous observations;
3. That for those houses showing considerable deformation, measurements be made of differential movement and of contributory vegetation and subsoil conditions;
4. That documentation of history of repairs or remediation be sought from owners or occupants; and;
5. That the ultimate objective of the research would be to identify design details that might be reasonably and economically incorporated to improve performance in future construction of low cost foundations in Regina.

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3 The Research Plan and Procedures

Contact lists of original addresses and names of homeowners were used as the bases for development of current lists compiled by referencing public telephone directories, land titles, and door-to-door inquiries.

Homeowners and/or occupants were contacted, informed of the objectives of the study and, if willing to participate, were interviewed using a questionnaire format (see Appendix A). Participants were asked about: length of their experience with the house; their observations of performance problems; their likes and dislikes about the house; any repairs made; their preference to have a basement; comfort in summer and winter; and; would they be willing to allow an indoor floor survey? In addition the interviewer completed a number of site specific observations pertaining to condition, occupancy, lot drainage and landscape features and a sketch showing pavements, shrubs and trees close to the house and any other noteworthy details on this and neighbouring lots. Photographs were also taken.

By appointment, level surveys of main floor surfaces were made in all permitted houses, including thirty-six slabs-on-grade (four of which were previously surveyed in the 1960's), one crawl space and one conventional basement for which measurements were made in the 1960's and 1970's. In total, thirty-eight floors were surveyed in 2003.

Test borings to obtain soil samples were strategically located near five slab-on-grade houses. Two test holes were drilled at each, one located adjacent to the highest and lowest perimeter points found by the floor surveys. Two sets of test holes were located for comparison with ground moisture conditions near slabs previously monitored starting in 1960. Another bore hole was located in a grassed test plot representative of an undisturbed soil profile subjected to natural precipitation in which ground movements at various depths were monitored during the 1960s and 1970s. Two other pairs of test holes were drilled adjacent to slabs where large trees had grown too close. In total 86 soil samples were taken from 11 boreholes. These samples were visually examined and tested in the laboratory for moisture contents.

More than one hundred houses were identified for possible inclusion in the study; current owner/occupants were sought out. Thirty-eight houses were selected for detailed measurements of foundation performance and five were selected for soil investigations. Selection of slabs-on-grade for detailed surveying were made in the following descending order of priority:

- Previously studied houses for which detailed surveying was carried out in the 1960's and 1970's;
- Houses with visible floor distortions, cracks, roughness, cracked or distorted partitions, binding doors or windows, or reported subfloor plumbing or heating duct problems, etc.;
- Houses reportedly having no problems but never-the-less suspected by the researchers to have experienced foundation movements; and,
- Houses considered to be representative of good performance and satisfaction of the occupants/owners.

Selected floor slabs were surveyed using an engineering laser level. Elevation contour plots of the floor surfaces were drawn, and the maximum deformations were calculated. The long-term performance of the foundations was then rated with reference to accepted engineering standards.

It would have been desirable to verify as-built reinforcing steel in the slab-on-grade foundations with non-destructive testing techniques. However, no economical test methods suitable to this study were available. Some photographs and reinforcing steel design plans were located and are included in Appendix B. It is believed they were originally permitted by Regina Building Department because of professional architectural/engineering design deemed appropriate for prairie soil conditions. Because of their innovative aspects, these foundations were subject to more than the usual inspections carried out by the City of Regina and CMHC at the time of construction.

Current Regina Building Bylaws require that all house plans submitted for approval include foundation drawings stamped by a Professional Engineer.

4 Summary of Data Collection

4.1 Questionnaires

From 112 selected addresses, 37 owners/occupants could not be verified, some houses were vacant, and others were either unavailable or unwilling to participate. A total of 75 Questionnaires were completed.

4.2 Floor Surveys

A total of 38 floors were surveyed.

4.3 Soil Moisture Surveys

A total of 11 boreholes were completed at 5 sites. A total of 86 soil samples were obtained and tested in the laboratory for water contents.

4.4 Analysis of Questionnaire Responses

Detailed analysis of the information gathered in telephone and face-to-face interviews and observations on-site are summarized in Appendix A. Of the 76 participants: eleven have lived in these homes for more than 40 years; and 38 have lived in these homes more than 10 years. The remaining 38 occupants have lived in these houses less than 10 years.

Long term residents offered the following positive factors in their satisfaction with their slab-on-grade homes: affordability of ownership; suitability for the elderly and the physically handicapped; accessibility; large lots; neighborhood (pride of ownership); trees and mature landscape; and no basement flooding problems. Some negative factors cited by the long term residents were: bedrooms, laundry and storage areas too small; ongoing repairs and maintenance of interior finish, doors, windows; difficulty, expense and recurrence of foundation rehabilitation with no guarantees of permanence; and difficulties in maintaining and upgrading heating and plumbing components.

Occupants with less than 10 years experience with these homes included first-time homeowners and renters of more youthful ages. Young families and singles liked the affordability. Accessibility was the positive for the elderly and physically handicapped. Families with more than one child found size of bedrooms, laundry and storage space limitations. Several occupants remarked that noise of the centrally located furnace was annoying.

4.5 Typical 1955 - 1960 Slab-0n-Grade Construction in Regina, SK.

See photos and design detail drawing in Appendix B.

For a typically level and flat lot in north west Regina, construction proceeded as follows:

1. Topsoil was stripped and lot rough graded for drainage, usually with a small front end loader;
2. Base for the 300 mm (12 inches) wide base of the slab perimeter beam was prepared at 150 mm (6 inches) below finished grade (See Plate in Appendix B);
3. Base for the interior area of the floor slab was mounded approximately 300 mm (12 inches) with compacted native soil and capped with 100 to 200 mm (4 to 8 inches) of sandy pit run gravel to bring to base of 89 mm (3.5 inch) thick floor slab. No interior stiffening beams of concrete were placed across central areas of the slab, but some thickening of the slab occurred where sand was displaced to accommodate installation of the sub floor heating ducts;
4. Polyethylene vapour barrier was placed over the shaped base;
5. Perimeter forms and heating ducts, interior feeder ducts were placed;
6. Perimeter and interior reinforcing steel was installed and tied at the design elevations see typical cross-section and plan layout in Appendix B.
7. Floor slab and perimeter beam concrete was cast monolithically and finished at design grade within +/- 6 mm (0.25 inches)
8. After perimeter forms were stripped, 50 mm (2 inches) thick insulation board was attached to the perimeter of the concrete slab. 13 mm (0.5 inches) thick cement parging was applied to the outside of the insulation;
9. No perimeter drain tile or coarse gravel fill were placed around the slab; and,
10. Backfilling to final grade was completed with native clay and topsoil.

4.6 Floor/Foundation Performance of Slab-on-Grade Houses

The performance of slab-on-grade foundations built in the 1955 through 1960 period in Regina can be divided into three time periods:

1. Early performance from construction to approximately five years of age;
2. Five to twenty or more years of age - depending on when tree and large shrub roots intrude below the slab; and,
3. Remainder of the life of the house.

4.7 Early Performance

Slabs-on-grade constructed following several summers of above normal rainfall were placed on soil profiles that were much wetter than normal. During the first few winters horizontal heat flow through these subsoils driven by heat loss from hot air subfloor ducts caused drying under central areas and wetting under perimeter areas. This resulted in settlement in central areas and heaving at the perimeters of floor slabs. This dish shaped deformation was more pronounced during heating seasons and diminished somewhat during the summers. By the third or fourth winter the centre of these floor slabs typically sagged from 30 to 80 mm (1.2 to 3.1 inches) lower than the perimeter. See Figure 5a (page 14), showing typical dishing during early performance.

4.8 Impact of Poor Surface and Subsurface Drainage

For slabs-on-grade constructed too low or on a lot with surface drainage towards rather than away from the house, occasional flooding and/or subsoil seepage impinging under one or more sides has caused differential heaving and sloping from one side to the opposite side or more complex compound slopes. See Figure 11 (page 20), which illustrates high centre and back of slab (rear of house) distortion caused by soil moisture being wetter at the back than at the front.

4.9 Impact of Tree and Shrub Roots Penetrating Below Slabs

Trees roots have been found to penetrate more than 4 m (13 feet) deep and to a radius larger than that of the overhead canopy. During extended drought periods and under sealed surfaces such as pavements and slabs, roots extend in search of moisture and cause deep-seated shrinkage. A bowl shaped depression surrounding a tree is the typical expression of this shrinkage. Figures 7 (page 17) and 8 (page 18) show this impact on two slabs-on-grade. The largest distortions were attributable to the combined influences of drying by deep roots and wetting usually from external sources around slabs.

4.10 Summary of Results of Floor Surveys

Of the 38 floors surveyed:

2 had more than 200 mm (8 inches) of differential movement

5 had more than 175 mm (7 inches) " " "

7 had more than 150 mm (6 inches) " " "

11 had more than 125 mm (5 inches) " " "

20 had more than 100 mm (4 inches) " " "

29 had more than 75 mm (3 inches) " " "

33 had more than 50 mm (2 inches) " " "

35 had more than 43 mm (1.7 inches) " " "

In other words all of the 35 slabs-on-grade surveyed had suffered more than 43 mm (1.7 inches) of differential movement.

In addition three more floors were surveyed for comparison with the slabs:

- a conventional wood floor carried on grade beams and piles over a crawl space;

- a typical wood floor over a conventional full depth basement; and,

- the ground supported concrete basement floor slab of the same house.

The wood floor over the crawl space experienced less than 20 mm (0.8 inches) of differential over 43 years of service.
The wood floor over the basement showed 54 mm (2.1 inches) of differential movement in spite of periodic adjustments of the teleposts over a similar service period.
The concrete basement floor slab in this house experienced 108 mm (4.2 inches) of differential heaving and 243 mm (9.1 inches) maximum movement over approximately 42 years.

4.11 Soil Moisture Surveys

For several of these houses the soil moisture conditions around the perimeter of the slabs was found to be much drier than measured in the 1960’s and 1970's. The deepest and most severe drying was found within the zone of influence of tree roots. During the course of this present study no flooding or extended periods of above normal rainfall occurred. In general, the region has experienced several years of below normal precipitation since 2000. A more complete review and analysis of rainfall and impacts on soil moisture can be found in Section 5.

4.12 Climate, Vegetation and Shallow Foundations

Regina enjoys a semi-arid cool climate with short hot summers. Total annual precipitation averages 377.6 mm (14.8 inches) of which 74% or 279.3 mm (11.0 inches) occurs as rain during the months of May through October (Environment Canada). This is less than half of the potential evaporation from grass-covered areas. Normal precipitation provides less than one third of the soil moisture needed to sustain a verdant mix of grass and trees desired by homeowners and urban planners.

Microclimatic impacts of urban development include: major warming, shading and surface moisture redistribution at the ground surface; roof and pavement drainage, snow clearing, and, irrigation. Within new perimeter subdivisions the effects of transformation from a rural agrarian to suburban land use are very significant on subsoil moisture balance. Surface pavements and roofs and land surface shaping generally all tend to hasten run off and reduce and reshape the natural infiltration of moisture from relatively uniform conditions of a flat prairie agrarian landscape.

In 1955-1960 when most of these flat slabs were built the accepted practices were:

1. Roof drainage was directed into the combined sewer system
2. No subsoil drainage tiles were provided around slabs-on-grade
3. No insulation was provided below slabs-on-grade
4. Minimal perimeter insulation was provided around edges of slabs-on-grade
5. Elevation of floor slabs was usually approximately at original prairie grade or less than 0.5 m (1.6 feet) above original grade with less slope away from house

provided at the rear of lots than at the front. In 2003 many of the subject lots had back-to-front drainage or ponding areas.

4.13 Subsoil Moisture and Precipitation

Annual precipitation varies considerably and averages 380.55 mm (15 inches) over the 113 years of records. Figure 1 shows annual total precipitation above or below the average precipitation for the period 1951 to 2003. The range in annual precipitation for this period was 394.4 mm (15.5 inches) with a high of 602.7 mm (23.75 inches) in 1954 and a low of 208.3 mm (8.20 inches) in 1961.

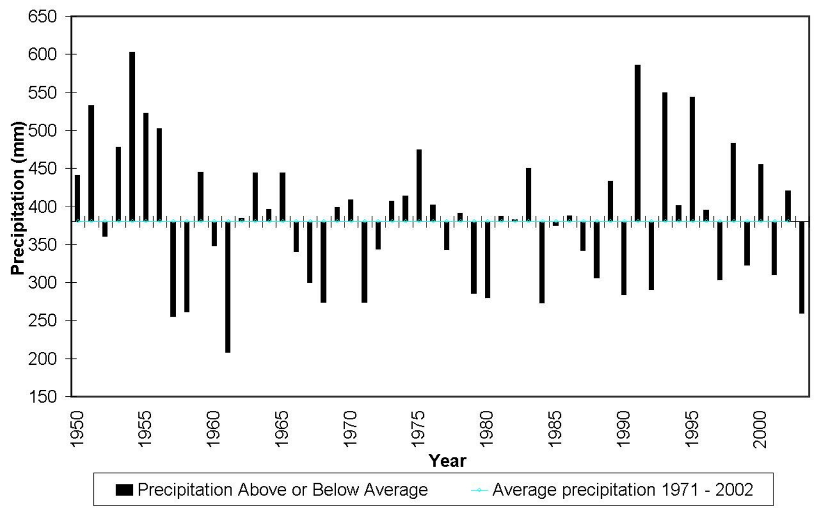


Figure 1 - Annual Precipitation for 1951 through 2003

Regina A Station Records, Environment Canada

Figure 2 shows cumulative departure from average precipitation as calculated from 1890 using Environment Canada records for Station A, Regina with the plot showing the period of interest to this study. By summing the annual total differences (departures) from long term average annual precipitation the Cumulative Departure (CD) From Long-term Average Precipitation is calculated. In 1954 the annual precipitation was 227.6 mm (8.96 inches) more than the long term average. By adding 227.6 mm (8.96 inches) to the CD of -244.3mm (9.62 inches) for 1953 the CD of –16.7 mm (0.66 inches) is determined for 1954. In 1955 the annual precipitation was 147.5 mm (5.81 inches) above the long term average, resulting in calculated CD for 1955 of +130.8 mm (5.15 inches). This form of data presentation illustrates short and long term trends in drier and wetter than average precipitation. Correlations have been found between Cumulative Departure From Average Precipitation and the average moisture content of undisturbed soil profiles under flat topography and native grass vegetation. Correlations have also been found with vertical ground movements under conditions of zero runoff or run on and native grass vegetation. The subsoil moisture profiles prior to construction in an idealized flat terrain with no net surface drainage (on or off) and unrestricted infiltration show correlation with precipitation history.

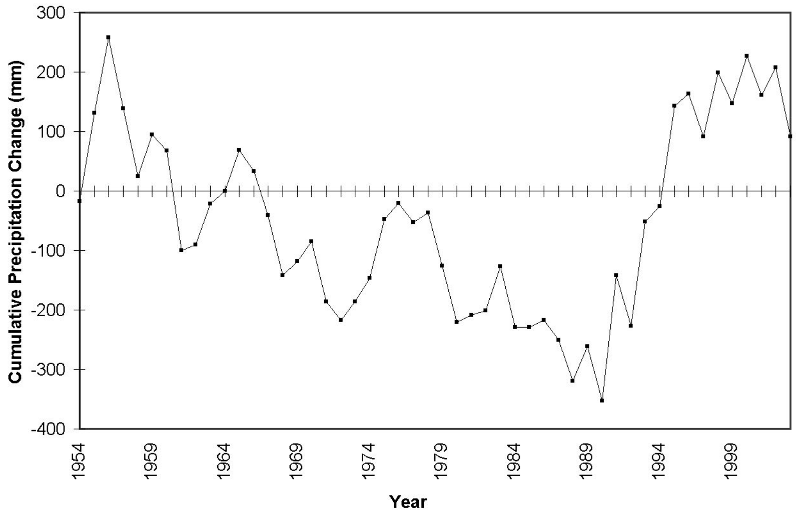


Figure 2 - Cumulative Departure from Long Term Average Precipitation

For 1954 through 2003, Regina A Station

Water ponding, melting of drifted or piled snow, and high variability of precipitation received at the ground surface add complexity to the water available for infiltration. Manmade constructions and practices further distort these patterns affecting the amount of moisture available for infiltration into unsaturated soil profiles. Plantings of deep-rooted perennial vegetation and landscape irrigation add further to the complexity of the infiltration/evapotranspiration budget of deep soil profiles. Leaks from plumbing and municipal services, heat loss from structures are other causes of variability of subsoil moisture. The probable extreme ranges for moisture content profiles under shallow foundations in Regina are illustrated in Figure 3. The boundary to the left is for long time severe drying within central areas of a heated crawl space. The boundary to the right is for long term wetting from the surface as might be caused by irrigation or surface flooding.

Slabs-on-grade provide sheltering and drying conditions under central areas and roofs shed water to the perimeter. Landscape irrigation or surface flooding can change the perimeter areas to moist and even wet conditions locally.

Trees can double the demand for subsoil moisture of grassed landscapes. Landscapers and gardeners try to create lush conditions by greatly increasing the amount of water delivered to the ground surface around shallow foundations. Mature deep-rooted vegetation usually is more efficient in extracting subsoil moisture within the root zone than can be supplied by infiltration through the overlying clay. Roofs and pavements greatly restrict and distort surface infiltration opportunities.

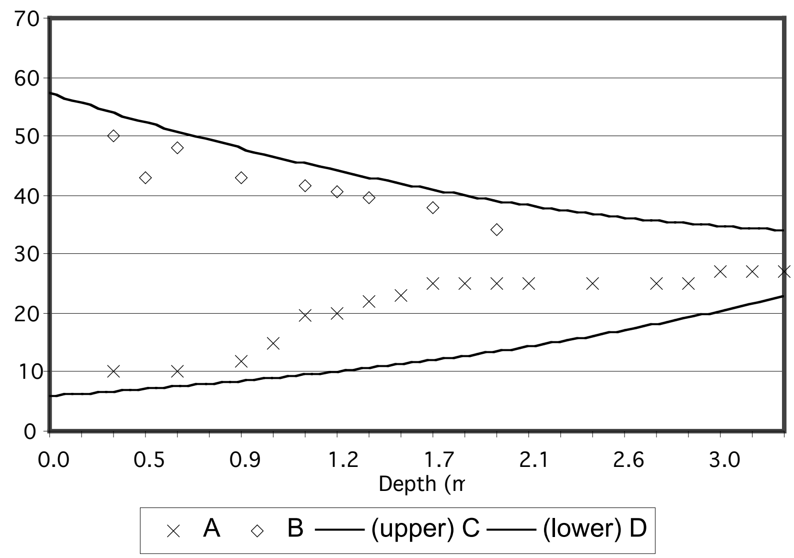


Figure 3 - Probable Extreme Ranges of Water Content for Undisturbed Regina Clays

A. Actual soil conditions after five years of heavy watering.
B. Actual soil conditions after ten years in an uncovered crawl space
C. Extremely moist conditions resulting from many years continuous surface flooding. (Hypothetical)
D. Extremely dry conditions resulting from many years exposure to 75°F and 20% relative humidity. (Hypothetical)

5 Slab-on-grade Performance Monitoring and Precipitation during 1955 Through 2003 Compared to 113 years of Records Back to 1890

Many of Regina's slab-on-grade houses were built in the 1955-1960 period. Annual total precipitation for 1955 was 523 mm (20.58 inches) and was 148 mm (5.81 inches) above the previous 65 year average annual precipitation of 375 mm (14.77 inches). 1954 had the greatest annual precipitation since 1890 totaling 603 mm (23.73 inches) or 228 mm (8.96 inches) in excess of the 65 years average. 1953 was also a wetter than average year with 478 mm (18.81 inches) or 103 mm (4.04 inches) in excess of the long-term average. 1956 was also a wetter than average year with 503 mm (19.79 inches) total precipitation.

Prior to construction in the summer of 1955, the rainfall received by unsheltered ground surfaces typical of undeveloped land in Regina area could be expressed as +83 mm (3.26 inches) cumulative departure from long-term average precipitation. From 1950 to 1955 the total precipitation received exceeded the normal by an average of 137 mm/yr (5.4 inches/yr) and a total of 689 mm (27.11 inches). Closer examination of daily rainfall and snowfall records and the actual dates of excavation and construction of the subgrade and base prior to concreting the floor slab would indicate the probable moisture condition of the subgrade clay at the time of capping with gravel and later when the concrete was placed.

Long-term above average precipitation periods set up wetting fronts which proceed downward from the surface. Well drained areas experience less storage of soil moisture infiltration. Intact, uncracked, compacted clay surfaces transmit less moisture than surfaces which are cultivated, loose, covered with gravel or other permeable material. Freezing and thawing and wetting and drying cycles tend to "open" the upper 1 to 3 m (3.3 to 10 feet) of the natural clayey soil profile. The profile becomes more or less unsaturated with the cracks and secondary structure of the subsoils containing more or less air depending on the ground temperature and availability of unfrozen water.

The year 1955 was generally wetter than normal with precipitation totaling 523 mm (20.58 inches) as compared to the mean total for 70 years (1890-1960) records of 383 mm (15.09 inches). Most of the precipitation occurred during winter, spring and early summer with August, September and October drier than normal. Slabs-on-grade constructed in early summer 1955 were placed over native clay subgrades with soil moisture profiles near their upper range for open field natural conditions.

In 1960 DBR, NRC began a field research program in which open field ground movements and floor slab movements were measured relative to deep bench marks driven into stable strata below the clay deposits. Also monitored were the soil moisture contents at depths ranging to 4.5 m (15 feet) below ground surface. A slab-on-grade house and property were
chosen for detailed study because of technical interest of its owner occupant, and, because of its location in terrain that was relatively undisturbed from its previous agrarian use. The grass covered test plot of Figure 4c was located in the rear yard of this home. The progressive heaving of this slab-on-grade is plotted in figure 4a and its dish shaped distortion is shown in figure 5a.

By the summer of 1960 the soil moisture profile for a grass-covered backyard with no large trees or shrubs nearby is shown as profile #1 on Figure 4c, August 24, 1960. By Aug. 21, 1962 the soil moisture profile (#2) showed the effects of two drier than average years. The moisture profile (#3) for July 16, 1964 is wetter in the upper one m (3.3 feet) and drier in the next m (3.3 feet) than it was in 1960. The soil moisture profile (#4) for the same location on Aug. 21, 2003 shows the added influence of a line of lilac shrubs approximately 3 m (10 feet) away.

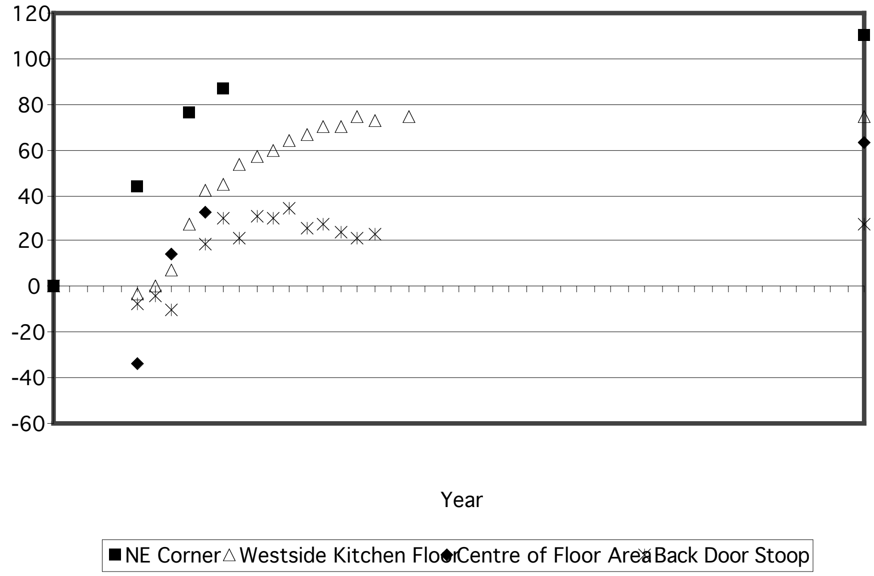


Figure 4a - Progressive Slab Heaving

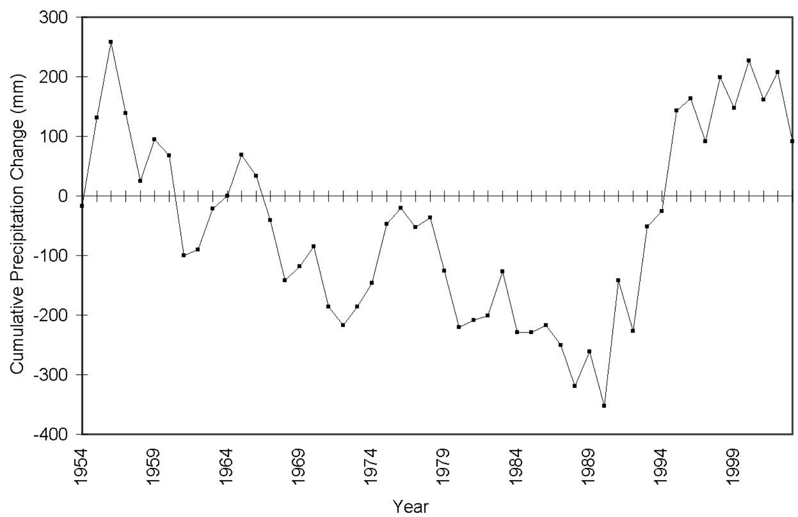


Figure 4b - Cumulative departure from Average Annual Precipitation

Calculated from 1890, Plotted from 1954 to 2003

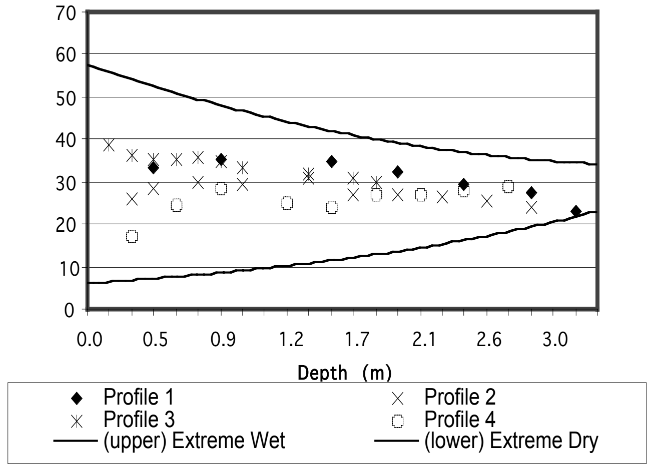


Figure 4c - Grass Covered Test Plot West Regina

Water Content Profiles
Profile 1 – August 24, 1960
Profile 2 – August 21, 1962
Profile 3 – July 16, 1964
Profile 4 – August 22, 2003

The soil moisture profile #5 on Figure 5b adjacent to the E corner of the slab-on-grade on the same lot was almost identical on August 22, 2003, to that of the grassed area near the back of the lot (profile #4). However, the profile #6 near the N corner of the slab was wetter at all depths and especially so below 1.2 metres (4 feet). See also Floor slab contours for July 1960 in Figure 5a and, progressive slab heaving in Figure 4a.

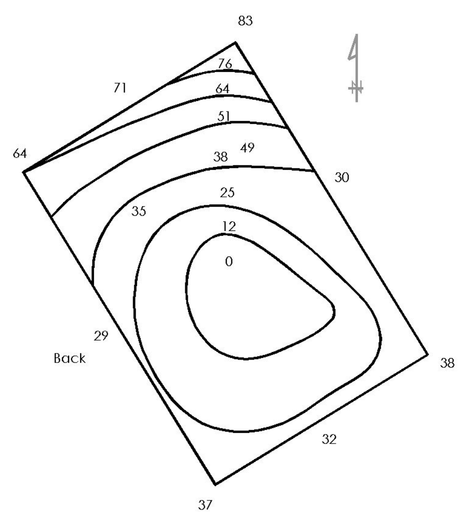


Figure 5a - Slab on Grade Dish shaped distortion July 1960

Slab Constructed October 1955
Surface Elevations and contours in mm

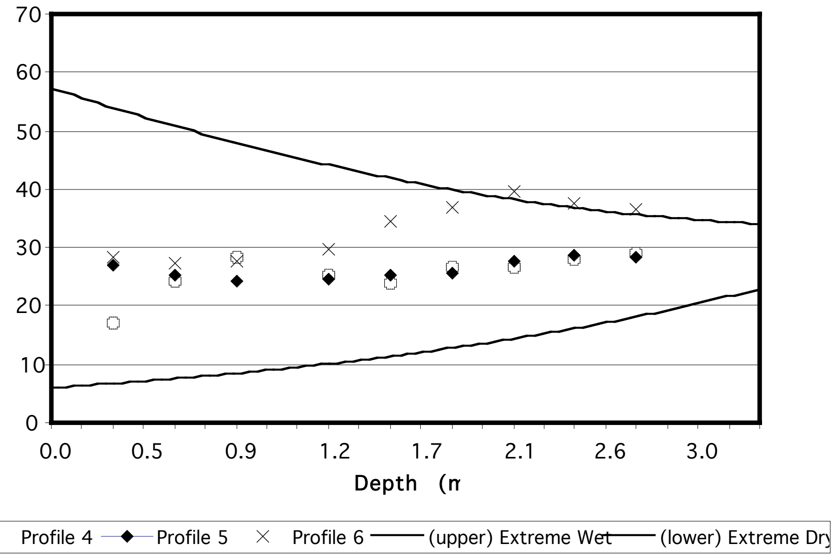


Figure 5b - Water Content Profiles on August 22, 2003

N and S corners Slab on Grade

See floor slab contours for the NW neighbouring slab-on-grade in Figure 6a. From a “dished” low centre in 1960, 43 years of irrigation of gardens at the south west side and lawn to the south side has supplied more water under the south half of the slab and caused 126 mm (4.96 inches) of differential movement from the centre of the west wall to the NE corner in 2003 (See figure 6b).

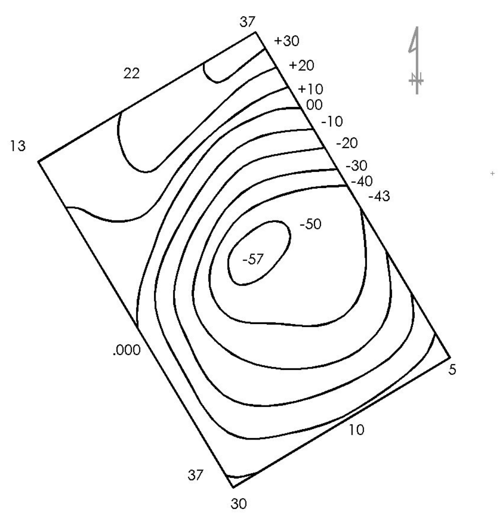


Figure 6a - Short Term Deformation of Slab Surface 1955 to 1960

Surface Elevations and contours in mm

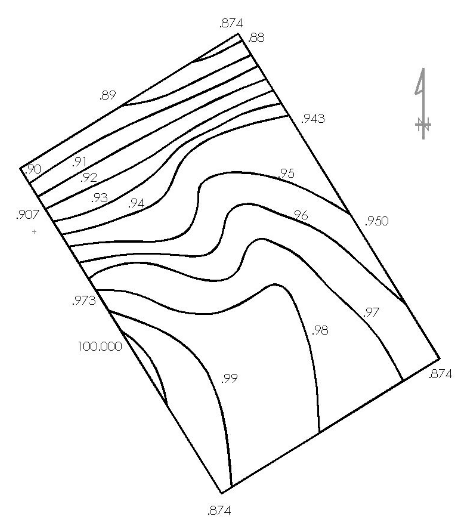


Figure 6b - Long Term Deformation of Slab Surface 1955 to 2003

Surface Elevations and contours in mm

The 5 year (1955 to 1960) and 48 year (1955 to 2003) distortions of the slab-on-grade house located on the northwest side of the first house are shown in figures 6a and 6b respectively. Figure 6c shows the soil moisture profiles at the N (#7) and W (#8) corners of the second slab-on-grade compared with the profile (#4) from the backyard of the first house.

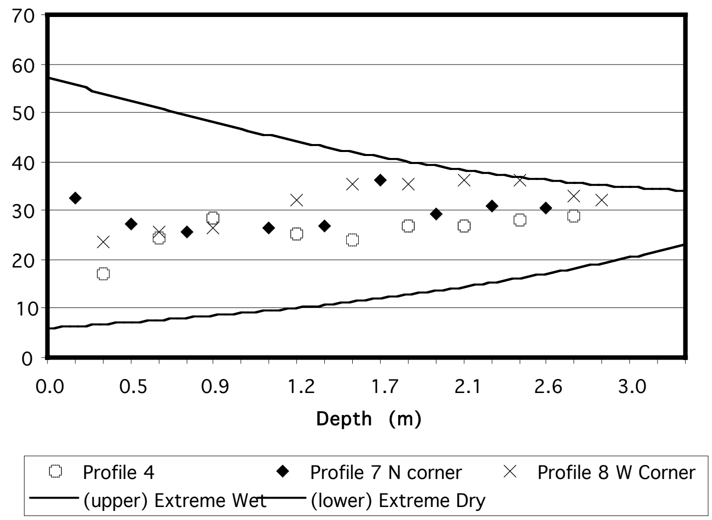


Figure 6c - Water Content Profiles on August 21, 2003 at NE and NW Corners

(See Figure 6b)

Figure 7a shows the back to front slope of a third slab-on-grade a few houses north on the same street as the previous two houses.

Figure 7b shows 2003 soil moisture profiles at the W (#9) and E (#10) corners of this third slab-on-grade compared again with the backyard profile (#4) from 1960. The higher moisture contents in the upper 1.5 m (4.95 feet) at the W corner are the result of lawn watering and the lower moisture contents at similar depths at the E corner are a result of a large tree growing too close to the house. See floor slab contours for this house on Aug.1, 2003 in Figure 7a.

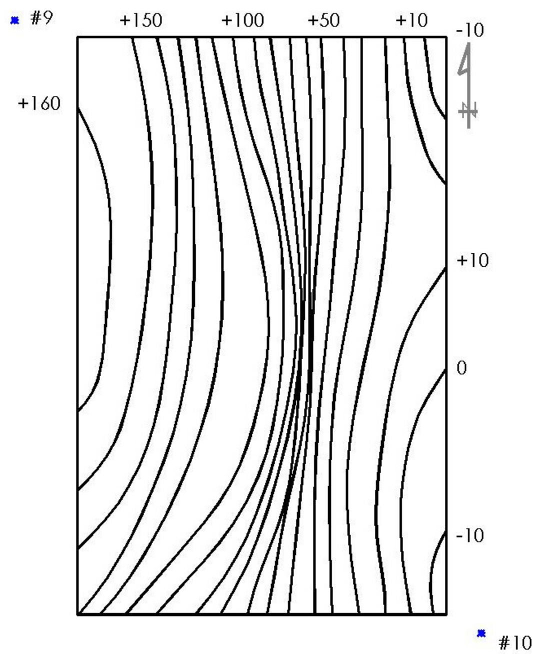


Figure 7a - Slab on Grade August 1, 2003

Surface Elevations and contours in mm

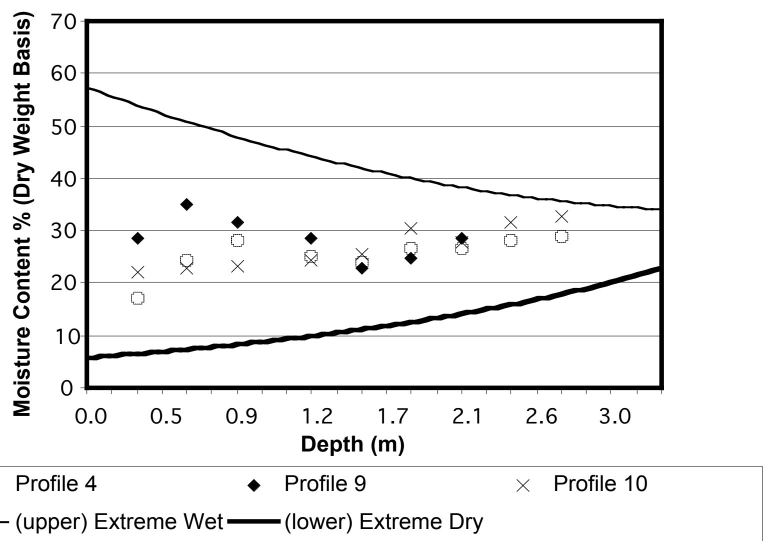


Figure 7b - Water Content Profiles on Sept 9, 2003 at NW and SE Corners

Slab on Grade
(See figure 7a)

Figure 8a shows floor slab contours for a house where several large trees on the neighbour's lot stand close and parallel to the south property line. Their root systems control soil moisture below the south end of the slab. Negative surface drainage from the back of the lot and from the neighbors to the north brings surface water periodically to the NW corner. Floor slab contours for this house measured on June 25, 2003 show a differential of 201 mm (7.9 inches) measured across the back of this slab.

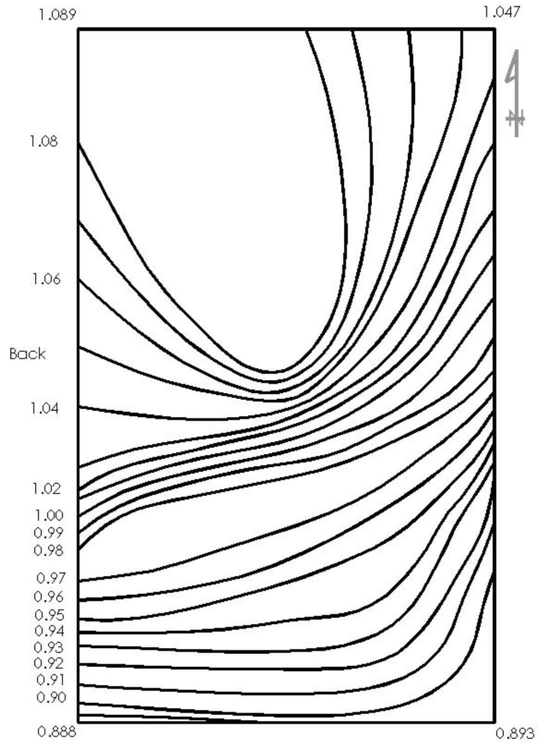


Figure 8a - Slab on Grade June 25, 2003

Surface Elevations and contours in mm

Figure 8b shows 2003 soil moisture profiles at the NW (#11) and SW (#12) corners of the slab shown in 8a. The 42% moisture content at 0.3 m (1 foot) on profile 11 was probably caused by rainfall preceding sampling on Sept 25, 2003

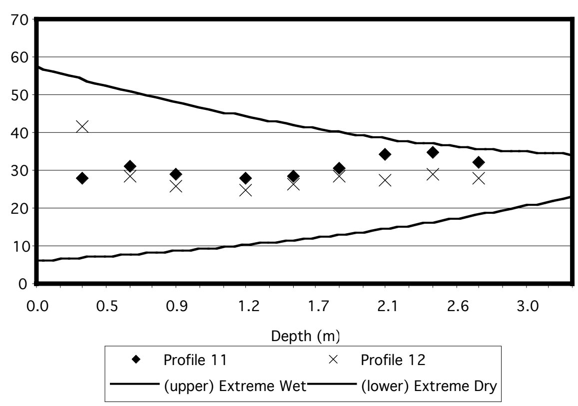


Figure 8b - Water Content Profiles on Sept 25, 2003 at NW and SW Corners

Of Slab on Grade shown in Figure 8a

Figure 9a shows floor slab contours and Figure 9b shows 2003 soil moisture profiles at the NW (#13) and SE (#14) corners of a slab-on-grade which is also supported by piles and grade beams. Many deep-rooted trees were planted within 2.7 m (9 feet) of the slab perimeter and have now grown to maturity. Large trees close to locations of test holes #13 and #14 dominate subsoil conditions even though the homeowner has directed roof drainage from each side of the house to the ground surface at these corners. Although the average soil moisture contents are very similar to those at #11 and #12 in figure 8b, the differential in elevations across this slab of 86 mm (3.4 inches) is less than half. (See Figure 9a) Interior damage to the house has been minimal and the homeowner is satisfied that the pile and grade beam foundations have greatly reduced damage that might have occurred with trees so close.

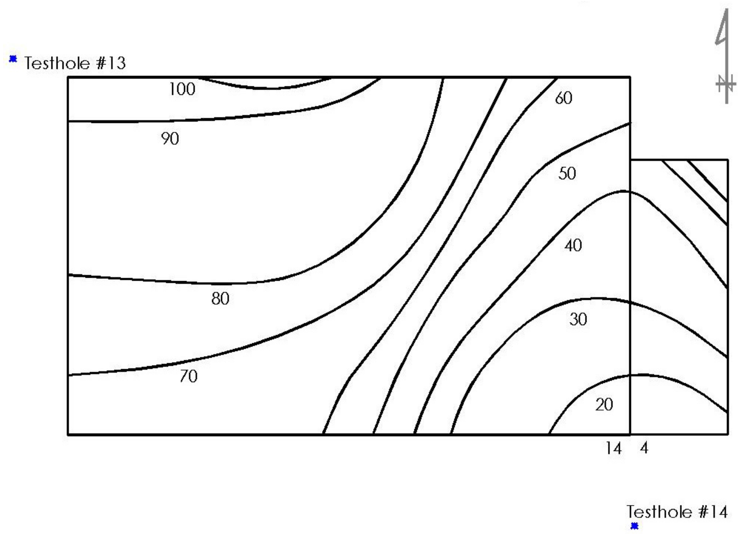


Figure 9a - Slab on Grade Influence of Several Large Trees

Slab Supported by Piles and Grade Beams
Surface Elevations and contours in mm

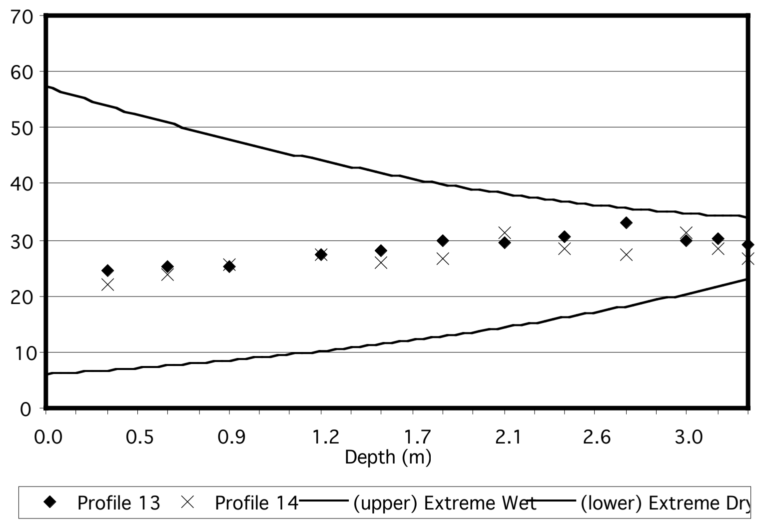


Figure 9b - Water Content Profiles on Sept 24, 2003 at NW and SE Corners

For slab shown on figure 9a

Figure 10 shows large differential heaving on the north side due to heavy lawn watering and settlement of the southwest corner due to a neighbor's nearby tree.

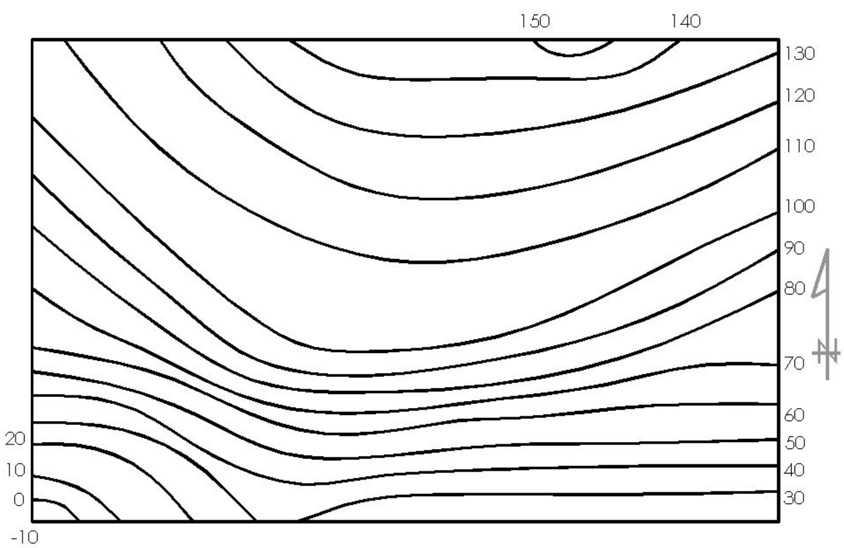


Figure 10 - Slab on Grade Front to Back Slope with Tree Influence

Surface Elevations and contours in mm

Figure 11 shows back and centre heaving due to poor surface drainage from the back of the lot.

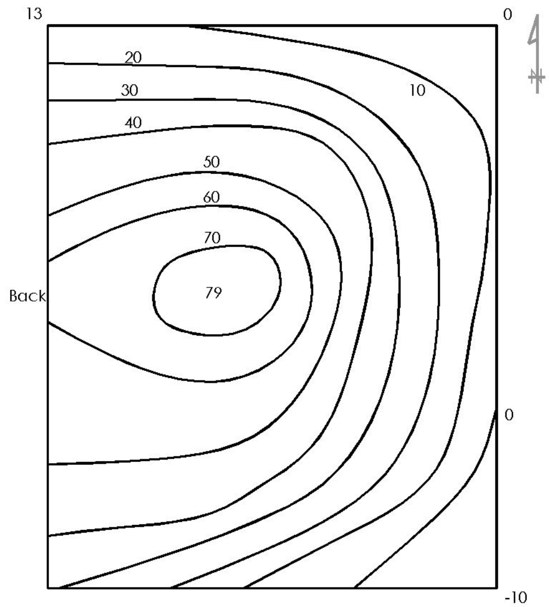


Figure 11 - Slab on Grade Back and Centre Heaving

Surface Elevations and contours in mm

5.1 Floor Surface Distortions Compared

In Figure 4a the progressive heaving of the concrete back door stoop, the surface of the kitchen floor, the highest (NW corner), and the lowest (centre) points on the floor slab are shown above a plot of Cumulative Departure From Average Precipitation (Figure 4b).

Floor level contours in Figure 5a for 1960 illustrate a nearly symmetrical dishing that many slabs-on-grade experienced during their first five years of life before trees, shrubs and other landscape influences became significant. By July 19, 1960 the differential between high and low floor elevations was 83 mm (3.3 inches). Heat flow from the perimeter and central heating ducts produced thermally activated soil moisture migration from the interior towards the perimeter areas of the floor. Soil shrinkage below central areas and swelling below perimeter areas caused differential movement of these ground-supported slabs.

In locations where irrigation of lawns or occasional surface flooding supplied excessive surface water, heaving of slabs sometimes proceeded inward towards central areas. (See Figures 5 -11 inclusive). Some homeowners reported seasonal reversals in floor movements, door and window jamming and plaster crack widths most commonly experienced during winters. As trees and shrubs grew large and within a radial distance from the slab less than their height, soil moisture extracted by their roots drove seasonal and long-term shrinkage of clay and settlement of ground-supported slabs.(See Figures 7, 8 and 10) The largest differentials in slab surface elevations were measured in houses where trees or large shrubs had caused large settlements of part of the slab and some wetting influence such as irrigation or flooding has caused heaving of another part of the slab.

5.2 The Impacts of Precipitation and Vegetation on Soil Moisture and Shallow Foundations

Starting about 1945 the long dry spell of 1927 through 1944 was reversed and the largest cumulative departure positive was reached in 1956 with 1953, 1954, 1955, and 1956 experiencing exceptionally high precipitation. 1956 marked the end of the longest above average precipitation period for Regina since records started in 1890 (cumulative departure reached +258 mm (10.16 inches).
Since 1955 the trends have been:

1. 1957, 1958 were much drier than normal
2. Until 1960, slabs were constructed over wetter than average profiles
3. Winter heating caused moisture to migrate towards edges and slab dishing results
4. 1961, 1968, 1979, 1980 and 1984 were much drier than normal
5. From 1983 through 1990 the cumulative departure from average precipitation grew to -352 mm (13.86 inches). Drying trend continues faster at the south and west half of houses that are not shaded
6. 1991, 1993, 1995, 1996, 1998, 2000 and 2002 all had higher than average precipitation and the cumulative departure from long term average decreased to +207mm (8.15 inches)

5.3 What Might Be Expected As Outcomes Of These Precipitation Trends?

Slab-on-grade floors placed in 1955 and 1956 experienced some central area settlements with perimeter area heaving resulting in maximum dishing in central areas over the period to 1960. Exterior area settlements and/or heaving became more pronounced through the 1970's and the effects of orientation to drying sun and prevailing wind driven precipitation, irrigation and drainage patterns, and the proximity of large trees and shrubs were increasingly significant. From 1979 through 1990 a general drying trend accentuated the settlements experienced in the 1970's with exceptions where local flooding or heavy irrigation caused heaving. 1989, 1991, 1993, 1995, 1998 and 2000 all had above average precipitation, which could have reduced or reversed the settlement trends with the exception of deep seated settlements due to trees and shrubs. 2001 and 2003 were drier than average.

6 Recommendations For Future Design And Construction Practices

How can we use climate information in better designing and building or is it only helpful in explaining past episodes?

6.1 Cumulative Departure From Long Term Average Precipitation (CD)

- Gives insight into trends in annual precipitation.
- Using the CD calculated for the date of construction of a slab-on-grade provides an index point with which past and future moisture profiles can be compared.
- The short term episodes of drier than average precipitation would be expected to have less impact on shallow foundations where homeowners increase irrigation and no deep rooted vegetation impinges on shallow foundations.
- Short term wetter than average conditions could have serious impact where surface drainage away from foundations is inadequate or reversed because of ground heaving or settlement.

6.2 Minimizing Impacts to Maximize Shallow Foundation Performance

1. Minimizing subsoil moisture-content changes:

   a) Maintain initial moisture content conditions over area and depth of influence of new structures. Recognize the impacts of shading by the building and vegetation on soil moisture demand.
   b) Regulate or eliminate water flow towards foundations: provide root barriers, perimeter drainage systems and adequate surface grading on all sides away from shallow foundations. Provide second lines of defense against moisture reaching subgrade soils from plumbing leaks and trench backups.
   c) Minimize heat losses into the subgrade and lateral heat flow under and outward beyond slabs

2. Working with subsoil moisture content and volume changes if clay expansion and/or shrinkage is inevitable:

   a) Use long term shrinkage and vegetation to minimize heaving against slabs which have been designed to function as structural units spanning settling or shrinking subgrades, eg, stiffened edge or pile supported designs.
   b) Use engineered fill to elevate slabs 0.5 m (1.65 feet) or more to increase subgrade loading, and, to promote better drainage away and more uniform moisture conditions below slabs.
   c) Use void forming techniques to eliminate heaving pressures against thin slab areas and increase bearing pressures under perimeter and rib stiffening beams.

d) Use pressure injected chemical slurries into dry and fissured subsoils to reduce swelling potential and to seal against moisture increase.

Long term drier than average periods coinciding with deep rooted tree growth present worst case conditions for shallow foundations. For example, foundations built in 1957 with deep rooting tree(s) planted nearby followed by 30+ years of progressively increasing departure from average precipitation and moderate lawn watering sufficient to keep grass from browning, produced very large distortion of shallow foundations, pavements and buried infrastructure. Conversely, the period 1991 to 1996 was a period of pronounced differential heaving adjacent to areas of ponding and infiltration compared to areas of water shedding or shielding.

Slabs built from 1955 through 1960 experienced:

- Initial differential movements of settlement in central areas and heaving at perimeters caused by subsoil moisture redistribution imposed by heat flow
- Followed by continuing perimeter heaving as landscaping and gardening irrigation augmented precipitation and reduced moisture deficits.
- Deep and wide spreading roots from trees and large shrubs gradually reduced subgrade moisture causing clay shrinkage and settlement of the overlying ground surface and shallow foundations.

7 Observations

All of the slabs-on-grade examined in this study suffered excessive differential movements by all code or engineering standards. Perhaps surprisingly, occupants of the houses were generally tolerant of conditions that might not be accepted elsewhere in Canada where volume-changing subsoils are uncommon. All of more than one hundred houses identified in 1960 are still in service. Occupants generally expressed levels of satisfaction taking into account the cost of occupying these homes either as owners or renters. Maintenance levels varied but generally were in keeping with other neighboring homes. Street appearance was generally good and most had undergone normal renewal and redecorating at the usual frequency for the type of exterior finish. The untrained eye would probably not detect the amount of distortion these houses have experienced. Many of these houses had also been redecorated at a frequency sufficient to remove unsightly plaster cracking. The floor surfaces, although sloping to varying degrees were generally tolerated by the occupants. A few of these houses have not been well maintained and will probably require major restoration work or replacement within the next ten years.

8 Conclusions

1) All of the slabs-on-grade examined in this study experienced large differential movements over service lives of 43 to 48 years. Of 35 floor surfaces surveyed, all had deformed 43 mm (1.7 inches) or more, 20 had deformed 100 mm (3.9 inches) or more and 2 had deformed more than 200 mm (7.9 inches).
2) In spite of large floor and superstructure deformations, all 112 houses originally identified were still in place and only a few were under renovation or appeared to be unoccupied.
3) Much maintenance and repair work of windows, doors and interiors had been done or needed to be done on most of these houses. Possibly a quarter of these houses have been mud jacked at least once. Some owners reported mudjacking had been carried out more than once. Their experience was that mudjacking did not eliminate movements, but improved performance over a period ranging from 7 to 10 years.
4) Information gathered in this study will be useful to designers and contactors contemplating the use of slab-on-grade construction for houses or other light structures in areas of soil and climactic conditions similar to those of Regina.
5) Geotechnical and foundation engineering capabilities have advanced greatly during the past five decades. Experienced specialists should be retained to advance the state of construction technology.

Appendix A1 – House Foundation Performance Survey

Date finished:__/__/__

House Foundation Performance Survey

Name:_______________ Address:__________________________

Owner:_______________ Phone Number:__________

Date Contacted:__/__/__
Date Visited: __/__/__

1.) How long have you owned/lived in this house?________________

2.) Have you noticed any of the following:

- Door/window jamming __
- Wall cracks __
- Floor movements __
- Other comments ______________________________

3.) What do you like most about this house design?
____
____
____.

4.) What do you like least about this house design?
____
____
____.

5.) Have any repairs been made in the last :

- 2 yrs ____ type of repair:______________________
- 5 yrs ____ type of repair:______________________
- 10 yrs ____ type of repair:______________________

6.) Would you prefer to have a basement in the house? Yes/No Why?
____
____.

7.) Do you find the house to be comfortable:

- in the winter ________
- in the summer _______

8.) Do you have any questions or comments?

____

____.

9.) If the floor slab is noticeably off level would you allow us to do a level survey inside your home? Yes/No

- Now_______
- Future appointment _________
- Call first before coming _______

Observations

Condition		Occupancy		Lot Drainage	
Well maintained		Senior(s)		Good. away from house	Y N
Average maintenance		Family		If not, why?____________	
				____________	
run-down		Single(s)		____________	
Unoccupied		Rental		____________	
		Owner		____________	

Landscape				
Lush grass				
Foundation planting				
Large shrubs	Number	Close	Distant	
Trees	Number	Close	Distant	
Dry landscaping				
Paved areas				
Attached garage				

Appendix A2 - Summary of Questionnaire Responses

Of the total 112 addresses identified all were visited, 31 were unwilling or unavailable to participate, and 4 houses were vacant or for sale.

Question 1: How long have you owned/lived in this house?

77 participated:

9 of these were original occupant/owners who had lived in the house 40 years or more

29 were long term residents who had lived in the houses 15 or more years.

40 had lived in the houses 10 or more years.

37 had lived in the houses less than 10 years.

Question 2: Have you noticed any of the following:

A. Door/Window jamming?	55 reported positively.
B. Wall cracks?	68 reported positively.
C. Floor movements?	46 reported positively.

D. Other comments? (few) including : "the floor of our addition is heaving", "we have ants in the winter"' and, inside doors don't close".

Question 3: What do you like most about this house design?

“all on one level”	12 responses.
“no basement”	10 responses.
“no stairs”	10 responses.
“inexpensive purchase”	8 responses.
“location and neighborhood”	7 responses.
“accessibility for handicapped and seniors”	7 responses.
“yard size”	6 responses.
“no flooding”	5 responses.
“floor plan, layout”	5 responses.

“easy to heat or cool”	4 responses.
“main floor laundry”	3 responses.

Question 4: What do you like least about this house design?

Out of 77 completed questionnaires the most frequent responses were:

1. concrete floor “hard and cold” mentioned by 5
2. low siting of floor surface has resulted in “flooding problems” during rainfall and/or spring melting of snow mentioned by 5 (interviewers observed many more situations of inadequate or negative slope to drain away from the homes)
3. “sloping floor is an irritation” mentioned by one but observable in many others
4. “no basement” mentioned by 3 but 21 more expressed a preference for a basement or crawl space in Question 6
5. “downflow furnace”, “furnace noisy in middle of house”, “upgrades and maintenance to mechanical and electrical systems not as easy” were 6 related comments
6. size of bathroom, laundry room, storage space were prime concerns of 4 but also given as reasons for preferring basements in 21 responses to Question 6
7. no adjustments possible by homeowner to relevel floor (no teleposts) mentioned by 4
8. excessive plaster cracking and maintenance costs mentioned by 1 but obvious in many
9. ants and bugs seemed to have easy access to interior and in-floor heat ducts and required exterminator services mentioned by 2

Question 5: Have any repairs been made?

A. In the last 2 years?

28 responses ranged from common maintenance for wear and tear to major renovations. Those that might be attributable to the slab-on-grade design and performance included excessive wall and ceiling plaster cracking, door and window adjustments, repairs and replacements, sewer scoped and cleared, wall and floor finishes replaced due to flooding from outside. One house was mudjacked to relevel in 2001, another in 2003.

B. In the last 5 years?

8 responses included replacing doors and windows, sidewalks, shingles, insulating ceiling in addition to common repair and maintenance procedures.

C. In the last 10 years?

9 responses included replacing door and windows, shingles and insulation, new furnaces and water heaters and 6 reported mudjacking and major renovations more than 10 years ago.

Question 6: Would you prefer to have a basement in the house?

A. A total of 23 responded in the affirmative with the following reasons given:

"more space"	12
"storage"	8
"children's recreation"	6
"furnace in basement"	2
"adjustments and upgrades easier"	2
"more homey"	1
"more options"	1

B. A total of 25 responded in the negative with the following reasons given:

"don't like basements"	9
"don't like stairs (or handicapped)"	11
"flooding concerns"	9

Question 7: Do you find the house to be comfortable:

A. In the summer?

B. In the winter?

Almost everyone interviewed indicated that the floor temperatures were acceptably comfortable summer and winter. Nine commented as follows:

Question 8: Do you have any questions or comments?

> "floor temperature is good"
>
> "the floor is surprisingly warm for concrete"
>
> "carpets on floor help with floor temperature comfort"
>
> "hardwood over concrete – no problem with coolness"
>
> "floor is cool but evenly distributed"
>
> "I like the infloor heating"
>
> "have 2 furnaces, floor temperature is good"
>
> "walls poorly insulated, heating bill is high, fan is on all summer"
>
> "has air conditioner in summer"

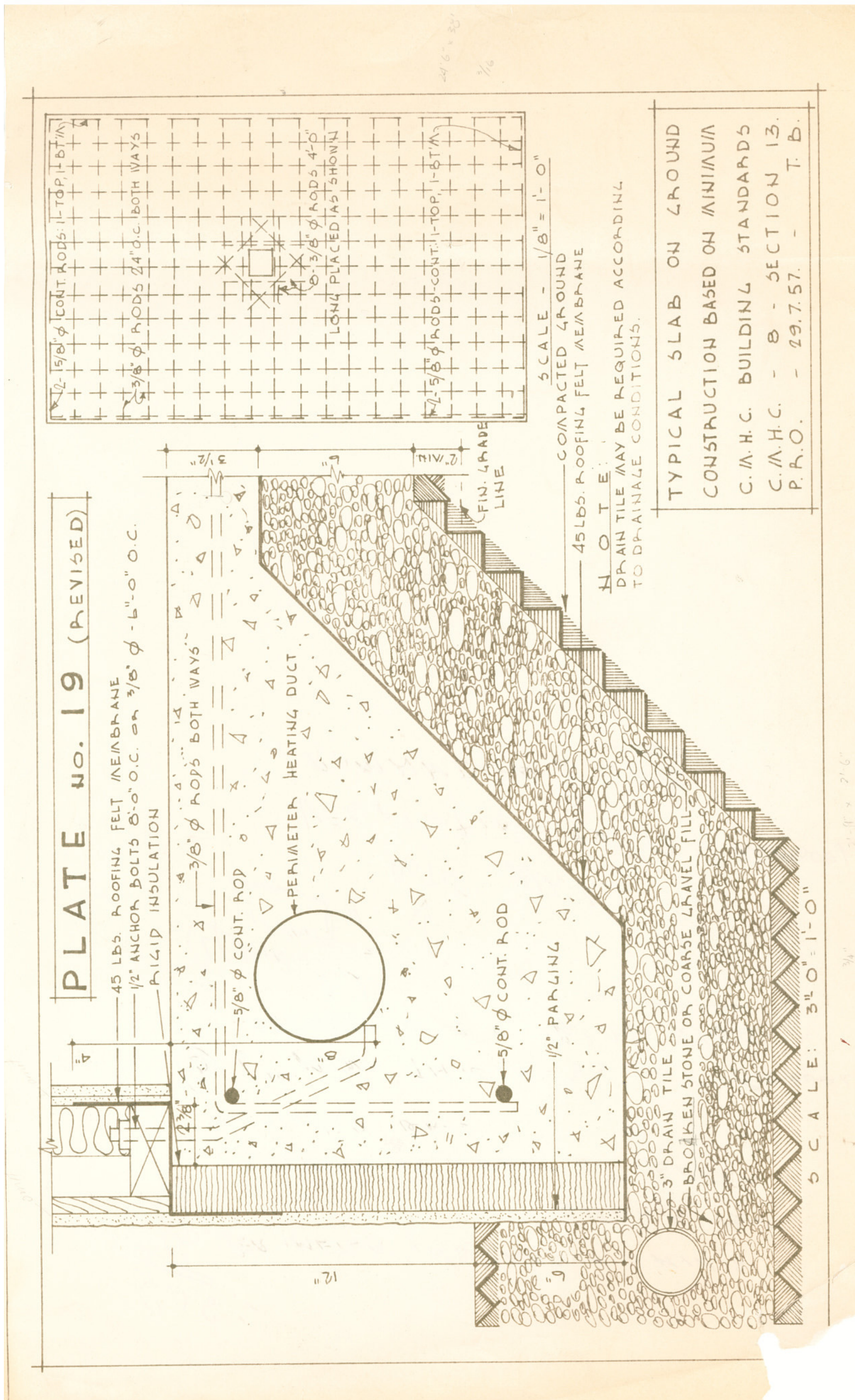
Question 9: If the floor slab is noticeably off-level would you allow us to do a level survey inside your home?

44 initially agreed, but 6 declined later for a total of 38.

29 initially declined with 6 more declining to total 35.

Appendix B1 - Typical Slab on Ground Construction

Based on Minimum CMHC Building Standards
CMHC 8 Sec 13 P.R.O. 29.7.57 TB



Appendix B2 – Photos of Slab on Grade Construction in Regina August 1960

Appendix B3 - Typical Forms, Reinforcing Steel And Heating Duct Layout Ready For Concrete

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