20-YEAR RESULTS OF AN IN-SITU MONITORING STUDY OF LARGE CONCRETE ELECTRICAL TOWER FOUNDATIONS AFFECTED BY ALKALI-SILICA REACTION (ASR)

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Abstract

In the late 1980's, a survey revealed that several of the concrete foundations built between 1965 and 1973 and supporting large critical electrical towers were affected at different levels by ASR. In 1991, a specific monitoring program was started to evaluate the behavior of some 30 repaired and non-repaired foundations. Surface deformation measurements along with visual periodic inspection were done from 1992 to 2000. Results showed that none of the products and repair techniques completely prevented the expansion, even the reconstruction method because a slightly alkali-reactive limestone aggregate was used in the new concrete. The main conclusion is that most of the concrete foundations show relatively similar rates of surface expansion after 20 years of monitoring than the ones observed during the first 8 years of monitoring. It is important to point out that none of the detected damage to the concrete foundation is considered to affect the overall structural integrity of steel towers.

Keywords: AAR, concrete foundations, long-term monitoring, repair methods

1 INTRODUCTION

Hydro-Québec is the largest energy producer in the Province of Québec (Canada) operating on a territory of 1.5 million km^2 and servicing 4 140 000 customers. It owns and operates more than 561 dams and control structures and 61 hydroelectric power plants. Its total capacity is 36 000 MW and total energy produced per year is 175 TWh (2014). The transportation of Hydro-Québec electricity relies on a large 735 kV electrical network of a total length of several thousand kilometers and also tens of electrical sub-stations that convert the high voltages to lower voltages. The most critical electrical towers of this network are the ones that cross the St. Lawrence River, near Québec City in Canada.

Those towers built in 1965-1966 and 1973 are anchored to large concrete foundations of several tens of cubic meters. The typical characteristics of these foundations are shown in Table 1. Field surveys conducted in the late 1980's and early 1990's revealed that a large number of these foundations are affected at different stage of deterioration mainly by a combination of alkali-silica reaction (ASR) and freezing and thawing. From 1992 to 2000, a program of long-term monitoring of expansion of repaired and non-repaired foundations was conducted and the results were reported in [1].

2 PROJECT DESCRIPTION (as previously described in Durand (2000))

The tower concrete foundations of 735-kV transmission lines that cross the St. Lawrence River near Québec City were built in 1965-66 and 1973 and are made from limestone and greywacke aggregates. In 1986, Hydro-Québec gave a mandate to a consultant firm to perform the condition assessment of these tower foundations [2,3,4]. The main defects consisted of:

- Swelling of the concrete foundations;
- Cracking of foundations and anchor blocks;
- Failure of a steel angle anchor bolt;
- Lack of conformity with the steel reinforcement and the maximum size of the coarse aggregate.

Major repair works were carried out in 1986-87. The work consisted of one or more of the following repair methods:

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- Removal of an external layer of cracked concrete and encapsulation with concrete and new steel reinforcements;
- Removal of an external layer of cracked concrete, splitting the upper part of foundations into two blocks and encapsulation with concrete and new steel reinforcement;
- Injection of epoxy resin into cracks;
- Confinement by placing steel frames, rods and plates held in place by anchors and/or epoxy resin;
- Application of a bituminous coating on the surface of the unexposed concrete (buried) and application of a flexible membrane on exposed concrete surfaces.

In the fall of 1991, ten core samples were taken from the reinforced-concrete tower foundations of the 735-kV transmission lines that cross the St. Lawrence River at Québec City and Île d'Orléans. It was noticed at that time that the degree of cracking was highly variable; for instance, the concrete made from limestone aggregate was usually cracked, while only one concrete foundation incorporating greywacke aggregates showed cracking. The 2012-2013 survey revealed that more foundations with greywacke aggregates developed a typical map cracking pattern [7].

Afterwards, it was recommended to pursue the monitoring of the repaired and non-repaired tower foundations. Thirty foundations were selected and their expansion was monitored from 1992 to 2000 and in 2012-2013 through the use of stainless steel studs inserted in the concrete surface combined with periodic visual inspections. It should be mentioned that the in-situ monitoring from 1990 to 1995 of some main damaged foundations at St. Nicolas near Québec City revealed a continuous trend of expansion and damage. These foundations were repaired in 1996 by removing the deteriorated concrete surface, anchoring, installing new steel reinforcement and casting new concrete (encapsulation).

In order to verify the evolution of deformation and deterioration of the foundations studied from 1992 to 2000, two new field inspections with expansion measurements took place in September 2012 and July 2013.

Figures 1 and 2 show location diagrams of the installations and indicates which foundations were instrumented along with expansion data. Figures 3 and 4 show typical towers. Figures 5 to 9 show typical cases of cracked foundations and Figure 10 illustrates a typical cracked steel angle with a ruptured bolt. Figures 11 and 12 present the typical aspect of polished concrete surfaces showing limestone aggregate particles with silica gel veinlets. Figures 13 to 18 show some foundations during and after repairs.

3 RESULTS

Firstly, one wanted to ensure that the data collected after an interruption of a decade could be reliably linked to the previous data set. Thus, the same extensometer as in the late 90s was used. Figure 19 illustrates that most foundations showed a fairly constant rate of expansion in the 90s and the new data are for the majority in very good agreement with the previous trends, as shown by the linear regression lines, thus indicating that the new measurements are reliable.

Table 2 presents the average annual expansion rates for the 4 categories of foundations investigated. Detailed results are presented in Table 3. Figures 20 to 23 present the linear regression curves obtained for the instrumented foundations.

Unrepaired foundations show expansion rates ranging from 0.0045%/year to 0.0280%/year, with an average value of 0.013%/year (N=3). Injected foundations show expansion rates ranging from 0.0096%/year to 0.0615%/year, with an average value of 0.024%/year (N=6) or 0.016% (N=5) without considering the very high result of 0.0615%. Foundations only covered with an impermeable membrane show expansion rates from 0.0046%/year to 0.0255%/year, with an average value of 0.015%/year (N=15). The foundation post-tensioned and covered with an impermeable membrane show expansion rates of 0.0122%/year. Finally, foundations that were split and encapsulated with new concrete show expansion rates ranging from 0.0037%/year to 0.0067%/year with an average value of 0.005%/year (N=5).

4 DISCUSSION AND CONCLUSIONS

Regardless of the type of intervention and according to the 2012-1013 measurements, the results show that in the large majority of cases, surface expansions related to the ASR continued at very similar rates to those measured from 1992 to 2000.

This long-time field survey also reveals that the average expansion rate varies significantly for the same category and same foundations of the same tower. For example, in the category "membrane", for 7007-5-1 and 7007-5-3 foundations, the average expansion rates are 0.023%/year and 0.019%/year, respectively. There are also large differences for 7008-5-3 and 7008-5-4 foundations versus 7008-5-6, with expansion rates of 0.0113%/year and 0.0093%/year versus 0.0224%/year, respectively. Considering that those are similar foundations close to each other, with the same reactive aggregate (globally, the reactive limestone beds are similar in the whole Québec City area), same cement and same mix design characteristics, it is difficult to explain such a difference. Differences in humidity and exposure conditions over decades of outdoor exposure could likely be the cause of those different behaviours, but this is only an assumption.

The visual observations allowed updating the previous information relating to each of the foundations, some errors on the type of intervention were indeed noted and corrected. Updated observations revealed the presence of non-listed cracked steel angles in several places. It was also noted that several of these steel angles were turn around and re-bolted on their undamaged side. Direct visual observations of some the most deteriorated foundations, regardless of the expansion rates measured, revealed that at some stage of surface crack widening, deterioration progresses rapidly with water infiltration and freezing action. Therefore, it can create large pieces of loosened concrete down to the first rows of steel reinforcement. Exposed or partially exposed steel reinforcements can also corrode and further increase the cracking and spalling of the exposed concrete surfaces of the tower foundations.

Based on all these results and observations of the 2012-2013 field survey and data compilation and analyses, Hydro-Québec relaunched in 2015-2016 a new campaign of core sampling and repair works on the most severely affected concrete tower foundations, **although none of the detected damage is considered to affect the structural integrity of the steel towers**. An engineering consultant firm was given a mandate to evaluate the long term durability aspect of these deteriorated foundations and to propose efficient repair techniques in order to extend their remaining service life.

5 ACKNOWLEDGMENTS

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TABLE 1: Typical characteristics of studied tower concrete foundations.

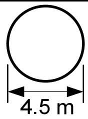
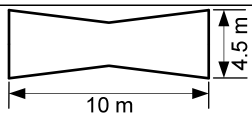
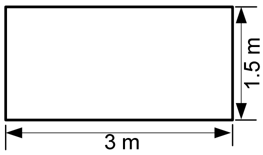
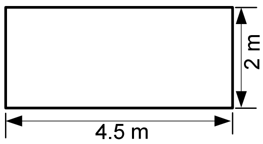
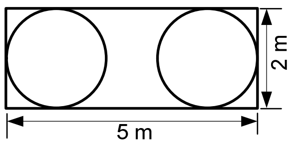
Type of foundation	Type of concrete	Reinforcement	Shape et size of horizontal cross section	Depth (m)	Example
standard	30-40 MPa air entrained	10M + 20M		4	St-Nicolas 7010-2-1
standard	30-40 MPa air entrained	10M + 20M		5	St-Pierre – Île d'Orléans 7007-4-1 et 2 (not instrumented)
anchor	30-40 MPa air entrained	10M + 20M		1,5 (bedrock)	Beaumont 7007-8-S
standard	30-40 MPa air entrained	10M + 20M		3	St-Laurent – Île d'Orléans 7007-5-1
standard : split and encapsulated	20-35 MPa air entrained	10M + 20M		4	Beaumont 7007-8-5 A and B

TABLE 1: Statistics of expansion rates of electrical foundations in the Québec City region and Île d'Orléans, from 1992 to 2013.

Type of intervention	Average annual expansion (%/an)	Coefficient of variation (%)	Maximum deformation over 25 years[1] (cm)
Unrepaired	0.013	78 (N=3)	2.1
Injected	0.024 0.016	74 (N=6) 30 (N=5)	4.6
Membrane	0.015	43 (N=15)	1.9
Split and encapsulated	0.005	20 (N=5)	0.5

Note:

1- Estimate based on maximum rates measured for each type, for a 3 m distance, considered as a nominal distance between two steel tower legs anchored into the concrete – for comparison purposes.

TABLE 2: Detailed statistics of expansion rates of electrical foundations in the Québec City region and Île d'Orléans, from 1992 to 2013.

Foundation	Treatment	Expansion		R^2
		%/year	µm/m/year	
7007-8-S	Injected[1]	0.0615	615	1.00
7023-2-3	Injected	0.0096	96	0.90
7023-2-4	Injected	0.0184	184	0.95
7023-3-1	Injected	0.0113	113	0.95
7023-3-3	Injected	0.0224	224	0.95
7007-1-S	Injected	0.0189	189	0.96
	Injected - Average	**0.0237**	**237**	
	Injected - Average[2]	**0.0161**	**161**	
7007-1-1	Membrane	0.0148	148	0.98
7007-5-1	Membrane	0.0223	223	0.99
7007-5-3	Membrane	0.0109	109	0.98
7007-8-2	Membrane	0.0105	105	0.98
7008-5-3	Membrane	0.0113	113	0.96
7008-5-4	Membrane	0.0093	93	0.97
7008-5-6	Membrane	0.0224	224	0.99
7008-8-2	Membrane	0.0046	46	0.87
7008-8-4	Membrane	0.0099	99	0.98
7008-8-S	Membrane	0.0126	126	0.90
7023-1-1	Membrane	0.0243	243	0.98
7023-1-3	Membrane	0.0255	255	0.99
7023-1-S	Membrane	0.0078	78	0.94
7023-5-3	Membrane	0.0200	200	0.99
7023-5-S	Membrane	0.0177	177	0.96
	Membrane - Average	**0.0149**	**149**	
7008-1-2	Unrepaired	0.0279	279	0.98
7010-1-5	Unrepaired	0.0047	47	0.91
7023-8-4	Unrepaired	0.0071	71	0.96
	Unrepaired - Average	**0.0132**	**132**	
7010-2-3A[3]	Encapsulated	0.0091	91	0.92
7010-2-3B[3]	Encapsulated	0.0126	126	0.96
7010-2-1A	Encapsulated	0.0051	51	0.69
7010-2-1B	Encapsulated	0.0073	73	0.84
	Encapsulated - Average	**0.0085**	**85**	
7007-5-2	Split + encapsulated	0.0044	44	0.87
7007-8-5A	Split + encapsulated	0.0067	67	0.91
7007-8-5B	Split + encapsulated	0.0043	43	0.84
7010-1-1	Split + encapsulated	0.0041	41	0.77
7023-5-4	Split + encapsulated	0.0037	37	0.68
	Split + encapsul. - Ave.	**0.0046**	**46**	
7010-1-S	Post-tension + Membrane	0.0122	122	0.97

Notes:
1- Foundation with cracks injected in 2001
2- Average deformation without the 7007-8-S result
3- Values obtained from 1992 to 1996. The foundations were repaired with new concrete in 1996.

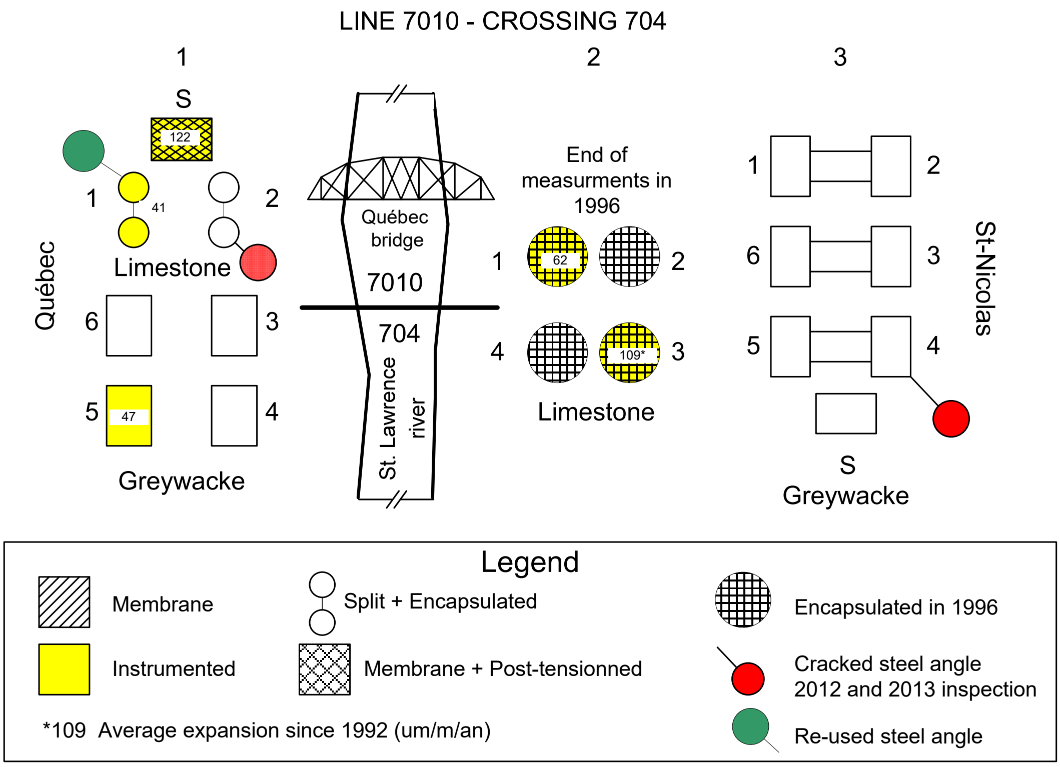


FIGURE 1: Location diagram of part of the tower foundations tested for this study (Québec City area - Interventions done in 1986-1987 unless otherwise stated).

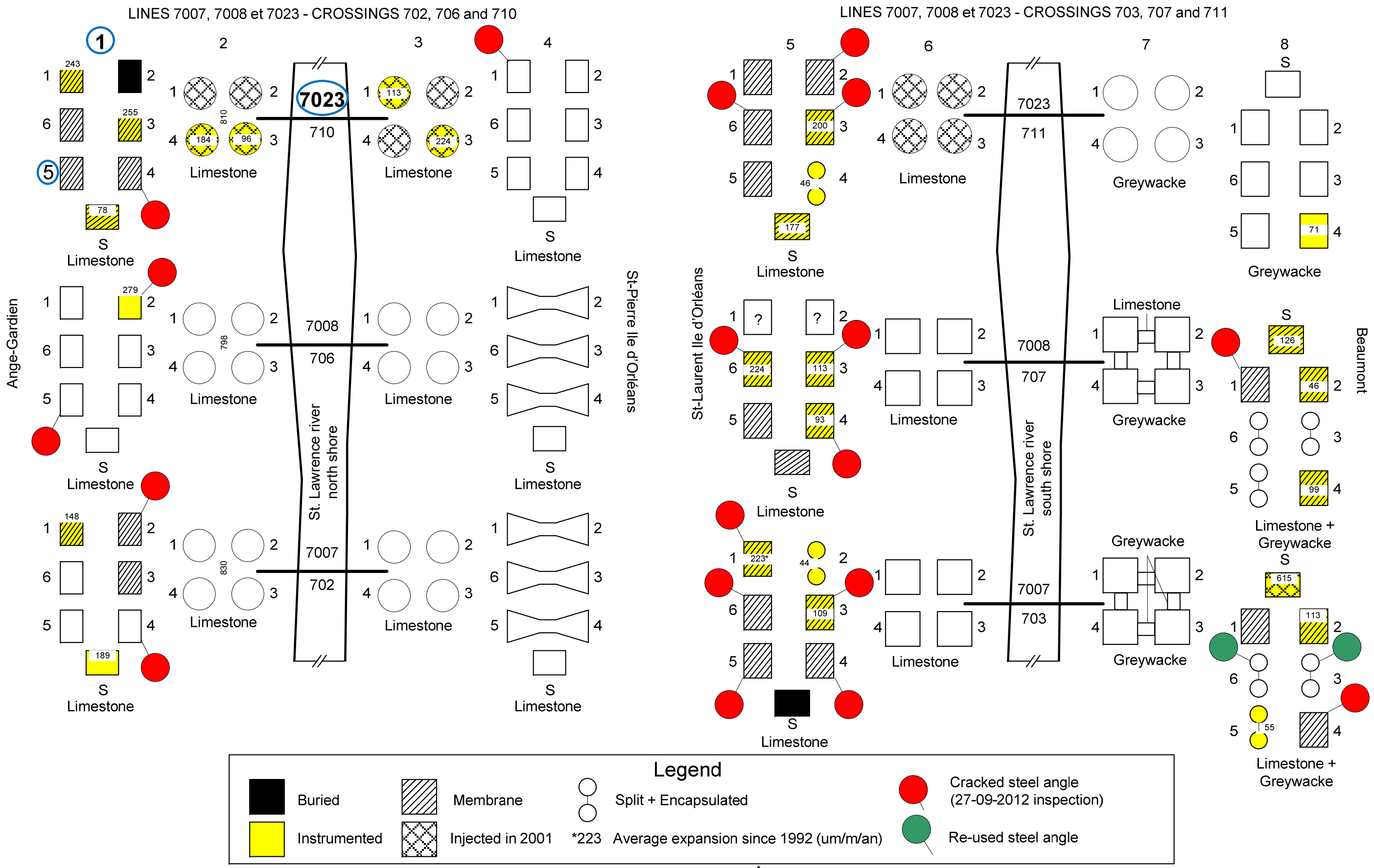


FIGURE 2: Location diagram of part of the tower foundations tested for this study (Île d'Orleans area - Interventions done in 1986-1987 unless otherwise stated)(Identification key : 70XX is the line, 2nd number 1 to 8 are localization of the towers and 3rd number 1 to 6 or S, is the individual ID of this tower foundation. Ex. 7023-1-5 highlighted in the three blue circles).

FIGURE 3: Typical electrical towers.

FIGURE 4: Typical electrical towers(actual height 120 m).

FIGURE 5: Example of a foundation injected in 2001 (2013 inspection).

FIGURE 6: Close-up of wide cracks (2015 inspection).

FIGURE 7: Example of a foundation covered with a membrane (2013 inspection).

FIGURE 8: Example of an encapsulated foundation repaired in 1996 (2013 inspection).

FIGURE 9: Example of a foundation with a greywacke aggregate (2013 inspection).

FIGURE 10: Example of ruptured bolt and steel angle (2013 inspection).

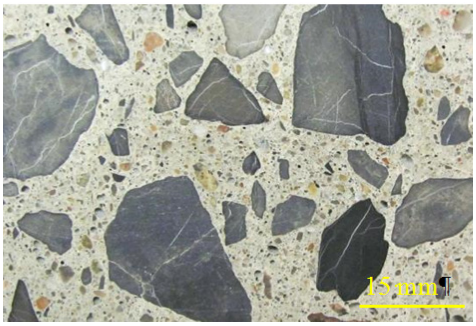


FIGURE 11: Limestone aggregates with multiple silica gel veinlets (polished surface) (2015 inspection).

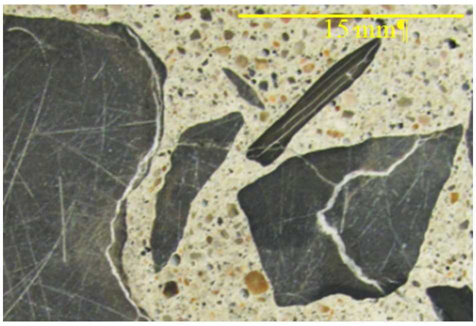


FIGURE 12: Limestone aggregates with multiple silica gel deposits (polished surface) (2015 inspection).


FIGURE 13: Example of repair works done in 1986-87 (splitting and encapsulation).


FIGURE 14: Example of a foundation under partial splitting (1986-1987 works).


FIGURE 15: Steel reinforcement in place (1986-1987 works).


FIGURE 16: Encapsulation with new concrete (1986-1987 works).

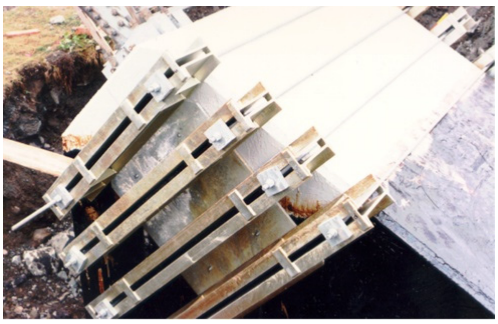


FIGURE 17: Example of a membrane and a post-tension frame (1986-1987 works).


FIGURE 18: Example of a membrane and a post-tension frame (1986-1987 works).

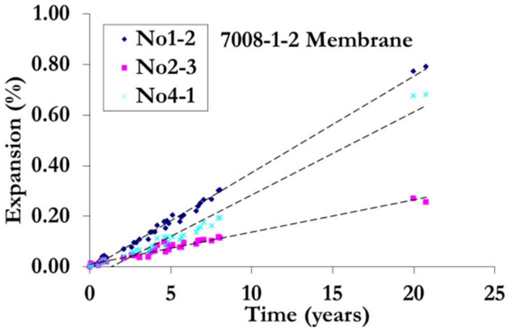


FIGURE 19: Example of deformation compilation measured from 1992 to 2000 and in 2012-2013.

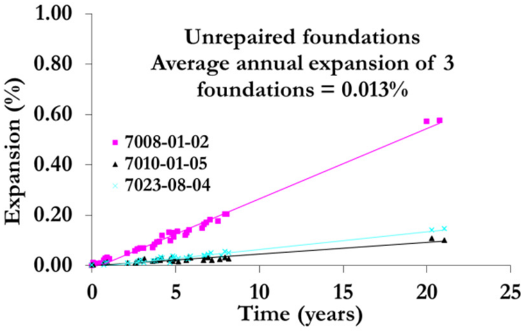


FIGURE 20: Linear regression curves of surface expansions of the 3 unrepaired foundations.

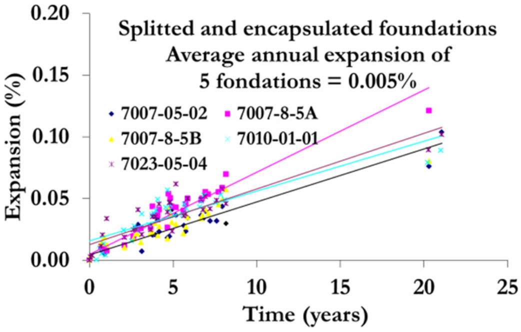


FIGURE 21: Linear regression curves of surface expansions of the 5 split and encapsulated foundations.

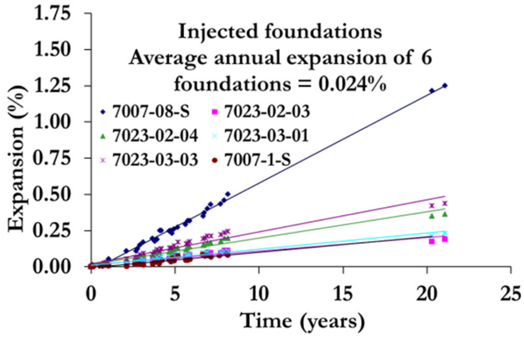


FIGURE 22: Linear regression curves of surface expansions of the 6 injected foundations.

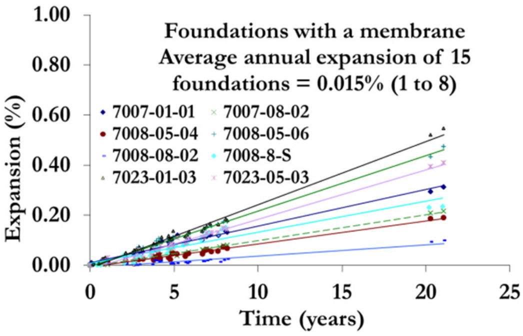


FIGURE 23: Linear regression curves of surface expansions of 8 out 15 foundations with a membrane.

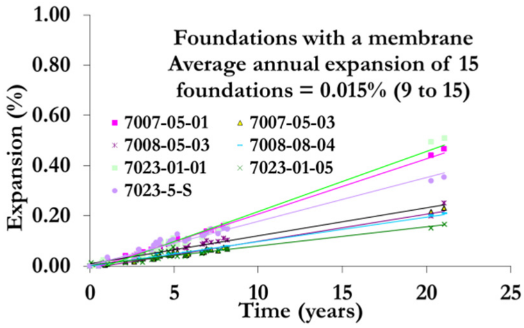


FIGURE 24: Linear regression curves of surface expansions of 7 out 15 foundations with a membrane.